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MHD POWER GENERATION FOR ADVANCED WEAPONS APPLICATIONS

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Final Report

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Advanced Weapons and Survivability Directorate
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KIRTLAND AIR FORCE BASE, NM 87117-5776

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13. ABSTRACT

A 15 MW_e magnetohydrodynamic (MHD) power system was designed, built, and tested. The technical effort was performed by a contract team led by Textron Defense Systems that included a Russian subcontract team led by the Institute for High Temperatures (IVTAN) of the Russian Academy of Sciences and Aerojet Corporation. The MHD power system, called the Pamir-3U, produced 15 MW_e of net output power from the three MHD channels of the system. The three plasma generator/MHD channel units are connected to an electrical circuit that provides electrical current to energize the magnet and delivers electrical current to the load. With this arrangement, a voltage of approximately 500 to 600 volts and a current of 25,000 to 30,000 amperes are delivered to the load.

A preliminary acceptance test program consisting of five power tests and several preliminary tests, was conducted during August 1994 at the Geodesiya Research Institute, Krasnoarmejsk, Russia. During this test program, power levels as high as 15 MW_e were obtained and various facility operating modes were demonstrated. The final acceptance test program, consisting of eight power tests, was conducted at Aerojet Corporation during February 1995. The acceptance test program was successfully completed, and the Pamir-3U MHD power system was subsequently accepted by and delivered to the Air Force.

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FOREWORD

This final report was submitted by Textron Defense Systems under Contract No. F29601-93-C-0033. The effort was sponsored by the Air Force Phillips Laboratory, Air Force Materiel Command, Kirtland Air Force Base, New Mexico with Dr. David W. Price PL/WSP as the Program Manager. Dr. Daniel W. Swallom, Judy S. Gibbs, Dr. Victor M. Goldfarb, and Dr. Isaac Sadovnik were responsible for the technical work. The work discussed in this report was performed by Textron Defense Systems, and two major subcontractors: The Institute for High Temperatures of the Russian Academy of Sciences and Aerojet Corporation.

The authors of this report appreciate the assistance given to them by the many individuals who contributed to the work performed on this report as well as the guidance given to them by USAF Program Manager, Dr. David W. Price of the Air Force Phillips Laboratory.

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1.0 EXECUTIVE SUMMARY

Magnetohydrodynamic (MHD) power generation systems offer the potential for portable, high power, pulsed power systems for a variety of military and non-military applications. The MHD power system offers the advantages of rapid start, high reliability, pulsed current output, and portable operation. The objective of this program was to deliver to the Air Force a 15 MW_e MHD power system that can be transported to a variety of terrestrial test sites. The program was a single phase program that included the design, fabrication, assembly, and test of the MHD power system. The activities also included a preliminary and final acceptance test program. The total duration of the technical program was twenty-seven months.

In order to perform this technical effort, Textron formed a team that included the Institute for High Temperatures (IVTAN) of the Russian Academy of Sciences and Aerojet Corporation. Other Russian organizations performing portions of the program for IVTAN included Nizhegorodsky Machinery Plant Production Association (Nizhny Novgorod), Lubertsy Research and Production Association (Soyuz), and Geodesiya Research and Development Institute (Geodesiya). This contract team performed all of the technical tasks of the program. The team was organized during October 1992, initiated their work in March of 1993, and completed their technical activities in March of 1995.

The design of the system was based on the previously well demonstrated IVTAN Pamir-2 MHD power system hardware. The Pamir-2 series was based on a two channel design. Because the requirements of this program required a higher power level, a third MHD channel was necessary. Thus, the system developed for this program was designated as the Pamir-3U MHD power system. The resulting MHD power system was assembled in Russia, where preliminary acceptance tests were conducted, and then shipped to the United States. Final acceptance tests were conducted at Aerojet Corporation, and the accepted MHD system was then delivered to the Air Force.

Figure 1 shows the layout and principal components of the Pamir-3U MHD power system. The main subsystem is the power unit, which consists of the solid propellant plasma generators, the MHD channels, and the magnet system. The electrical equipment unit (EEU) consists of the contactors, disconnectors, and a magnet protection system. The initial excitation system (IES) contains the batteries used to provide the initial magnet current and the battery charger. The dummy load resistance provides a load for the output power of the system, and the control, measuring, monitoring, and recording system (CMMRS) is used to operate the system and to record the data obtained during operation. The entire system, except for those items requiring separate transportation for safety reasons, can be mounted on a single flat bed trailer for transportation to a variety of test sites.

The Pamir-3U MHD power system produces 15 MW_e of net output power from the three MHD channels of the system. Each of the three plasma generator/MHD channel generators are connected to an electrical circuit that provides current to energize the magnet and delivers current to the load. Two of the MHD channels are connected in parallel and these two are connected in series with the third generator. With this arrangement, a voltage of approximately 500 to 600 volts and a current of 25,000 to 30,000 amperes are delivered to the load. Approximately 800 to 1000 volts and 14,000 to 18,000 amperes are delivered to the magnet. This current produces a central field in the magnets of 3 to 4 Tesla. All plasma generators are fired simultaneously, and the plasma generator operating times are identical. Depending on the plasma charge initial temperature, operating times of six to ten seconds are possible.

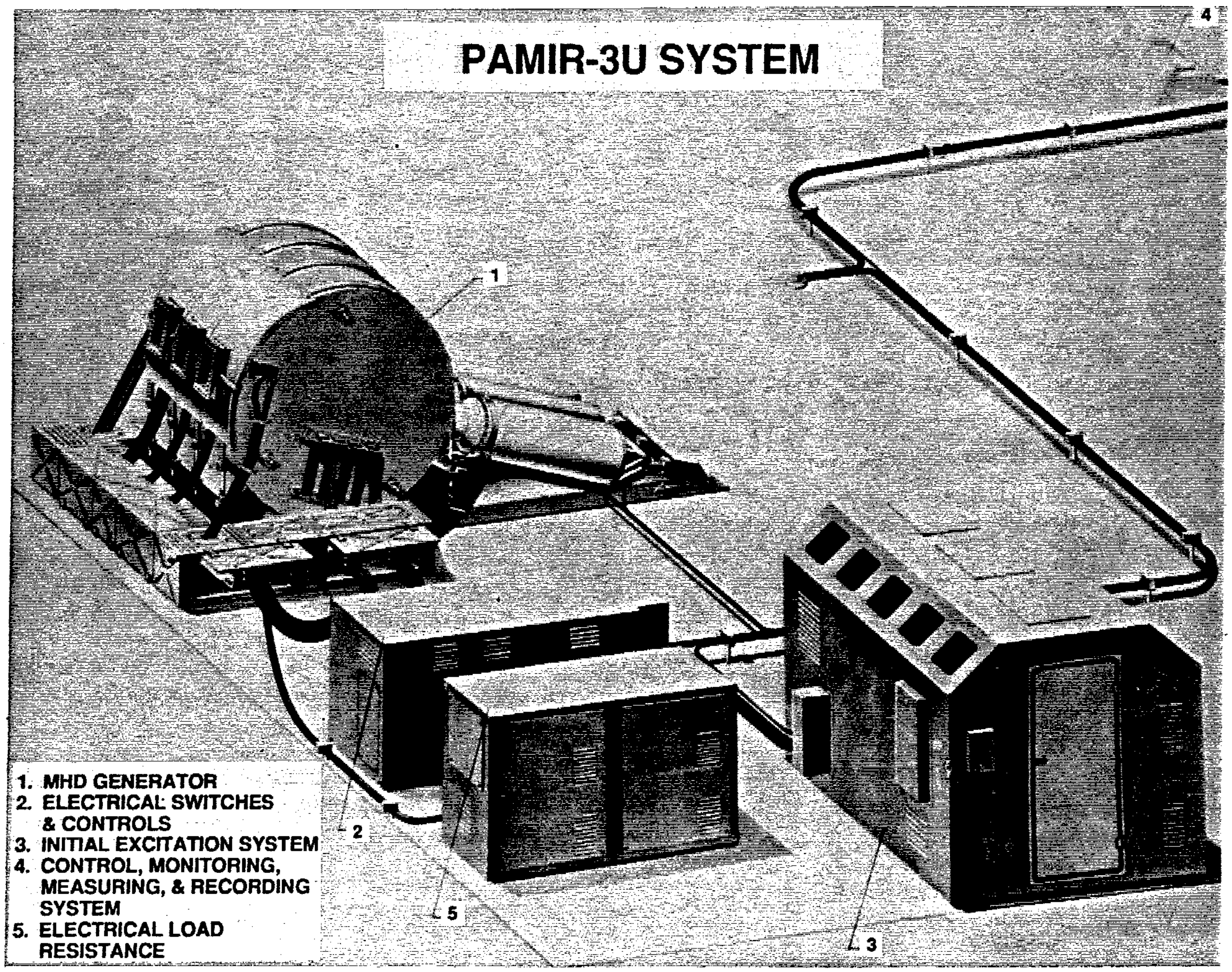

Figure 1 Pamir-3U MHD System

A preliminary acceptance test program, consisting of five power tests and several preliminary tests, was conducted during August 1994 at Geodesiya. During this test program, power levels as high as 15 MW_e were obtained. Operation of the facility in different operating modes was demonstrated, and several tests were conducted where the resistance was varied during the hot-fire test run. These tests demonstrated that all of the features of the system were functioning properly and that the technical requirements were satisfied. At the conclusion of these tests, the equipment was disassembled and packed for shipment to the United States, and the final acceptance test program.

After ocean transportation from St. Petersburg, Russia to Norfolk, Virginia, and transcontinental shipment by truck to Sacramento, California, the Pamir-3U MHD power system was delivered to Aerojet Corporation for final acceptance tests. The final acceptance test program consisted of eight tests. This program included high power tests (~15 MW_e), nominal power tests (10 to 13 MW_e), and maximum duration tests (~10 MW_e). The testing was successfully completed within three weeks and the Pamir-3U MHD power system was accepted by the Air Force. Also included in the acceptance test program was a training program to provide the United States personnel with the necessary information for operation, maintenance, service, and repair of the Pamir-3U MHD system. By the conclusion of the acceptance test program, the United States personnel were performing all of the required activities.

The Pamir-3U MHD power system is shown in Figure 2 installed on Test Stand P-2 at Aerojet. The test stand was built for solid rocket motor testing and easily accommodated the Pamir-3U MHD power system and associated equipment. The test stand is supported by a remote command and control installation, where the CMMRS was located. The power unit, consisting of the plasma generators, MHD channels, and magnet system is shown in the center of the photograph. The electrical equipment is located just behind and to the left of the power unit. In the background, the large unit is the IES. To the extreme right of the photograph is the dummy load resistance. The overall size of the components can be derived from the magnet coils, which have an overall diameter of approximately two meters.

The program results that have been achieved to date have shown that the Pamir-3U MHD power system can satisfy the technical requirements and reliably deliver the necessary power. The power system was operable for each of the scheduled tests, and achieved the planned test parameters. The overall results of the program have demonstrated that portable MHD power systems are feasible, that the required power levels can be achieved, and that reliable operation is possible. Based on these successful results, MHD power systems should be favorably considered for any military or non-military pulsed power application requiring high current, relatively low voltage power.

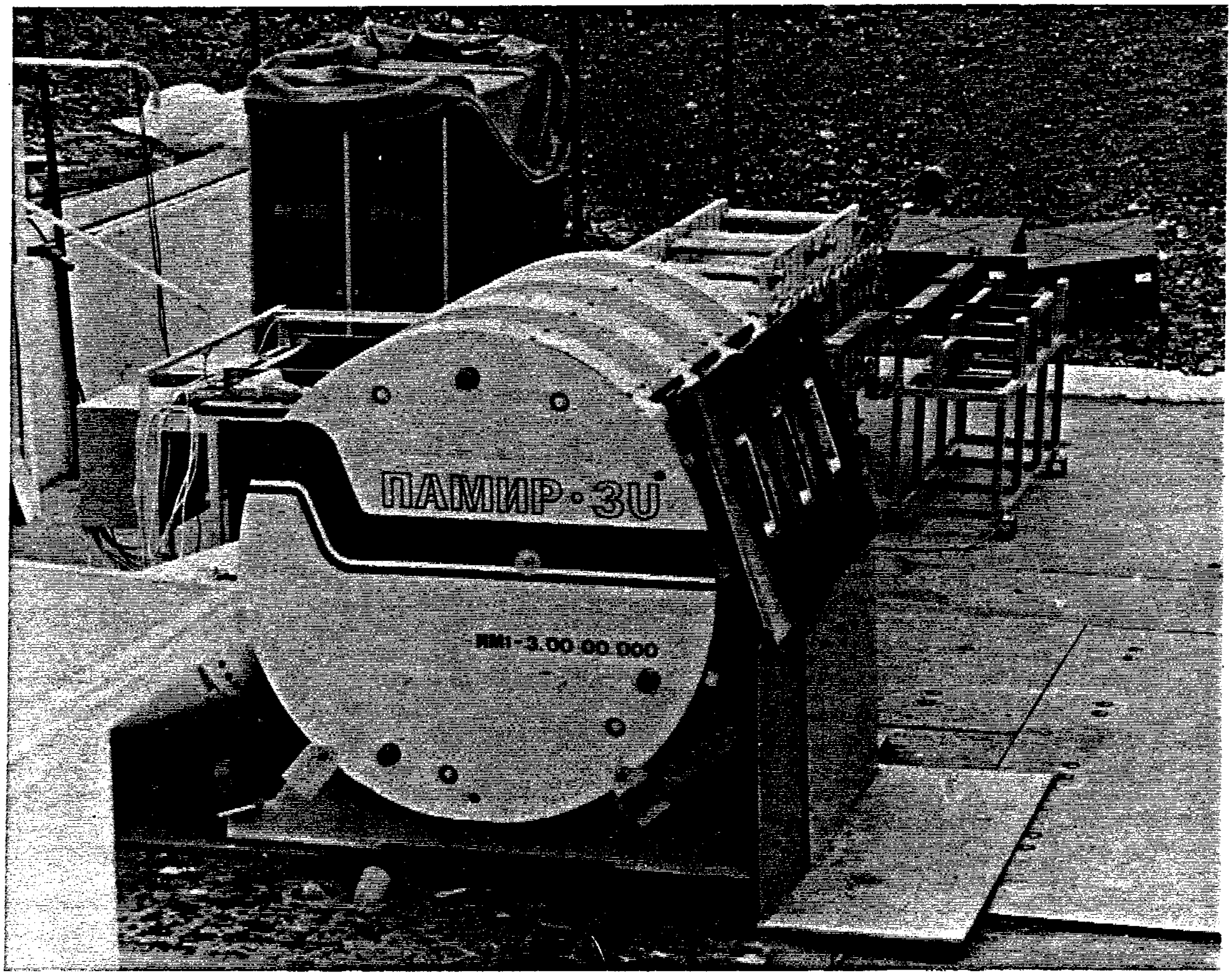

Figure 2 Pamir-3U MHD Power System at Aerojet Test Site

2.0 INTRODUCTION

2.1 PROGRAM DESCRIPTION

The MHD Power Generation for Advanced Weapons Applications Program consists of twenty tasks, which have been grouped into four major tasks: 1) Program Management; 2) Data; 3) Safety; and 4) MHD Power Generation. Table 1 lists each of the twenty tasks, along with the Statement of Work (SOW) task number and the Work Breakdown Structure (WBS) task number. The end result of this development program is an operational 15 MW_e portable MHD power system for use in providing electrical power for advanced weapons applications. In addition, the development, analysis, and testing activities of this program established a sufficient engineering data base for further MHD power generator development.

The overall program was a twenty-seven month technical effort with a three month final report period. The program elements include the design, fabrication, assembly, test, and delivery of the 15 MW_e transportable MHD power system. In addition, safety and environmental tasks were a major part of the program. Operational and safety permits were required and were obtained for operation of the MHD power generator at the United States acceptance test site. The overall program schedule is shown for each of the twenty tasks in Figure 3. The task structure in the schedule and the task duration correspond directly to the Statement of Work and reflect the completed work schedule.

In addition to the technical requirements of the program, numerous contract data items were supplied. These include the deliverable items shown in Figure 4 as well as eight quarterly review meetings. Two of the quarterly review meetings were also designated as the First and Second Required Progress Briefings. In addition, eleven interface meetings were held during the program. Five of these meetings were held in Russia, and six were conducted in the United States.

2.2 PROGRAM PARTICIPANTS

In order to perform the program described in the report, Textron elected to combine the technical expertise and resources of the two largest developers of MHD power systems in the world - Textron Defense Systems and the Institute for High Temperatures of the Russian Academy of Sciences (IVTAN). Textron Defense Systems, formerly known as Avco Research Laboratory, has been the leader in the United States for the development of MHD power systems for military and utility applications for nearly thirty-five years. IVTAN, the leading agency in Russia for the development of MHD power systems has manufactured over ten portable power systems ranging in net electrical output power from 5 MW to over 40 MW. IVTAN has been supported in this MHD development work by the Nizhny Novgorod Machine Building Plant and the Lubertsy Scientific and Production Association Soyuz. These systems have been under development since the late 1960's and have been used for a wide variety of military and scientific purposes. A third team member, Aerojet, provided the test site for demonstration and performance verification tests in the United States. Aerojet is a major developer, manufacturer, and operator of solid, liquid, and hybrid rocket engines in the United States. Preliminary acceptance testing was performed at the Geodesiya Research Institute in Krasnoarmejsk, Russia.

The major emphasis of this program was the delivery of a 15 MW_e MHD Power System for advanced weapon applications as well as the resolution of key technical issues and uncertainties

that could impact the future deployment of larger MHD power systems. The team members performing this multimegawatt MHD design, fabrication, and testing program are described in the following sections.

TABLE 1
TASK IDENTIFICATION WITH STATEMENT OF WORK AND WORK BREAKDOWN STRUCTURE

WBS TITLE	WBS NO.	SOW REFERENCE
MHD Power Generation For Advanced Weapons Applications	0.0	0.0
Project Management	1.0	3.1
Data	2.0	3.2
Safety	3.0	3.3
Personnel Safety	3.1	3.3.1
System Safety	3.2	3.3.2
Environmental Safety	3.3	3.3.3
Radiation Safety	3.4	3.3.4
Explosives Safety	3.5	3.3.5
MHD Power Generator	4.0	3.4
Reliability	4.1	3.4.1
Systems And Subsystems Analysis	4.2	3.4.2
First Required Progress Briefing (FRPB)	4.3	3.4.3
Second Required Progress Briefing (SRPB)	4.4	3.4.4
System Integration	4.5	3.4.5
System Performance Demonstration	4.6	3.4.6
System Performance Verification	4.7	3.4.7
MHD Generator Delivery	4.8	3.4.8
Training	4.9	3.4.9
Repair Parts	4.10	3.4.10
Completion Of Technical Performance	4.11	3.4.11

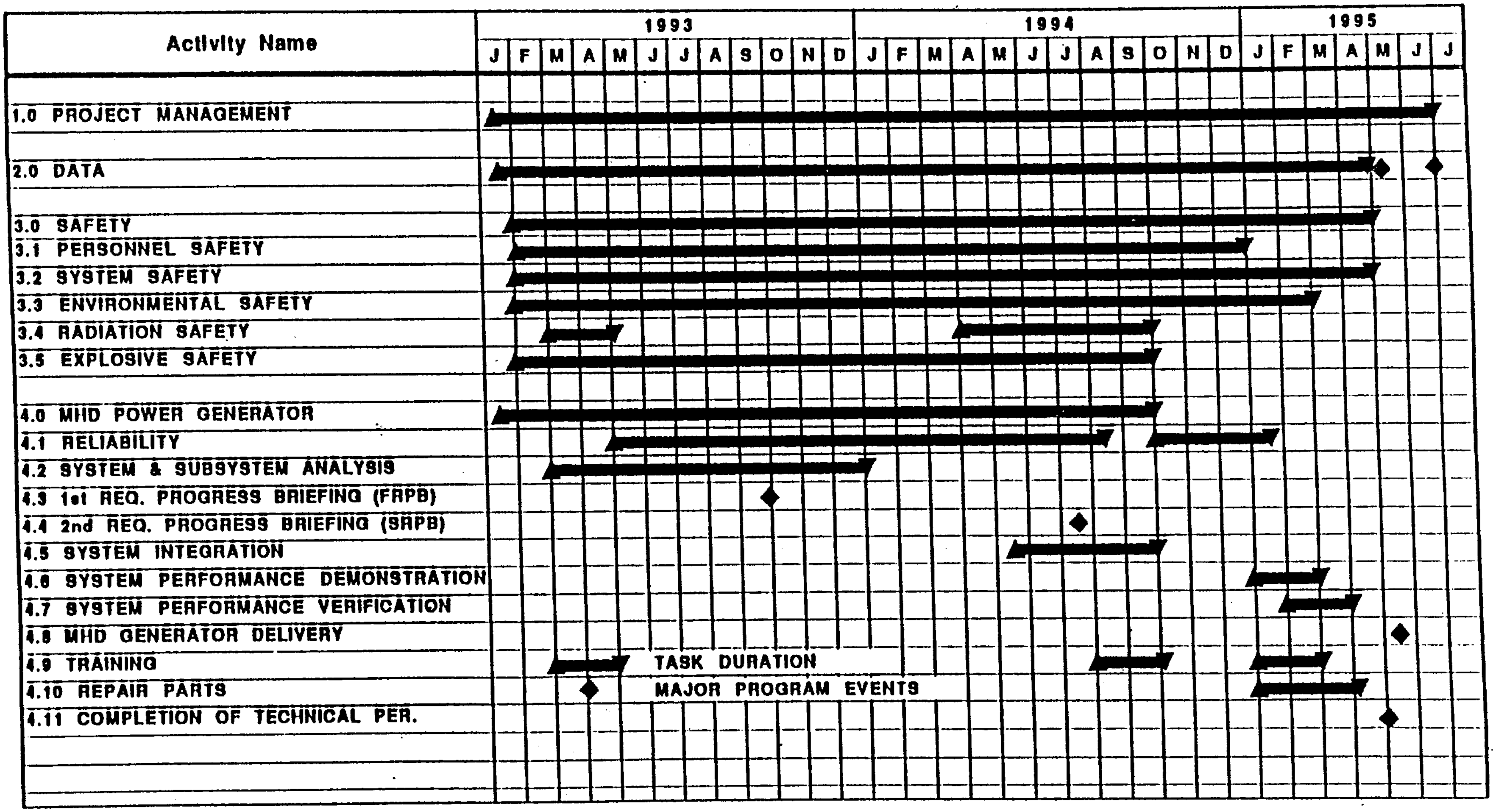

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Figure 3 Program Schedule

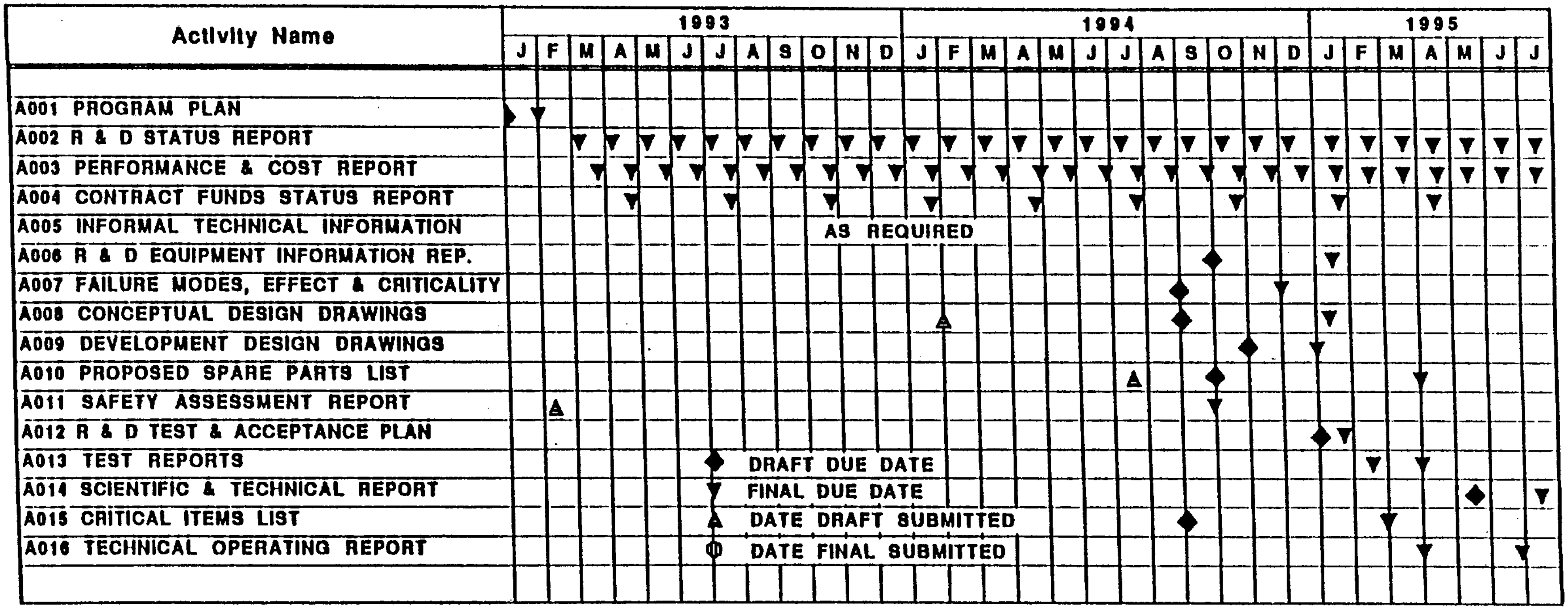

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Figure 4 Delivery Schedule for CDRL Items

2.2.1 Textron Defense Systems Inc. - Prime Contractor

Textron Defense Systems (Textron) is a high quality developer and producer of affordable weapon systems and related products for defense operations. The Division was founded in the mid-1950's to take on the United States Air Force challenge of solving the technical problem of protecting ballistic reentry vehicles during the re-entry into the earth's atmosphere. In the late 1970's the technical innovation of Textron Defense Systems was extended to meet the needs of conventional forces with a focus on smart sensor fuzed munitions. In 1991, the Electronic Systems business line was formed, composed of specialized surveillance systems, landing systems, communications antennas, and high precision accelerometers and inertial gyros.

The Strategic Systems product line expanded and matured in the 1980's with contracts for the design and development of the entire Peacekeeper reentry system consisting of the nose cone, deployment module, and associated electronics. Textron also took on the manufacturing challenge of Peacekeeper by expanding its manufacturing facilities for the production of the MK21 reentry vehicle.

The Tactical Systems business has a primary focus on the design, development and production of smart munitions, which are based on the sensor fuzed warhead technology. These include the Sensor Fuzed Weapon (SFW), the smart Wide Area Mine (WAM), the development of the Anti-Helicopter Mine, and a versatile submunition (DAMOCLES) that can search a large area and acquire targets which may be difficult to locate.

The Electronic Systems business has a variety of major products. First are surveillance systems, which are engaged in the research, development, operation and maintenance of specialized surveillance systems. Another major area is the Automatic Carrier Landing System (SPN-46) being delivered to the United States Navy. An extension of this technology in landing systems is the Mobile Microwave Landing System, which is designed for high reliability and rapid deployment.

Opto Electronics, located in Petaluma, California, is also part of Textron Defense Systems. Opto Electronics is a leading infrared detector manufacturer of lead sulfide and lead selenide detectors qualified for a number of military applications worldwide, including detectors for the Textron Sensor Fuzed Weapon.

Energy Technology, which was part of the Avco Research Laboratory, Inc. until its consolidation into Textron Defense Systems in 1990, has the largest and most experienced industrial MHD professional staff and the most comprehensive industrial MHD test facilities in the United States. Textron has demonstrated the most experience in the design, construction, and operation of both military and utility MHD generators in the United States. Textron has conducted both military- and utility-oriented MHD development programs for over thirty-five years.

Textron was responsible for the overall program management and systems integration. Specific major tasks performed include preparation, editing, and assembly of all contract deliverable documentation including the final report; import, transportation, environmental compliance, export control certification, and permits; transportation in the United States; supervision and overall conduct of the test programs; and overall interface among all program participants and appropriate government agencies. Textron was also responsible for system and subsystem analysis.

2.2.2 The Institute for High Temperatures of the Russian Academy of Sciences

The Institute for High Temperatures of the Russian Academy of Sciences (IVTAN) is one of the leading research establishments in Russia in the field of thermal physics and new power-generating processes. The main fields of investigation are: the physical properties of solids, liquids, and gases at high temperatures, thermodynamic properties of low-temperature plasmas, physical gas dynamics, and electro-physics.

IVTAN was among the first organizations to study direct energy conversion. Studies in the field of MHD physics, the theoretical and numerical investigations of gas and electrodynamics of plasma flows under magnetic and electric fields, heat and mass transfer as well as engineering and design in the field of high-power energetic devices brought fame to the Institute. During the more recent years, new problems such as the economy and ecology of energetics, energy conservation, non-traditional fuel and non-traditional energetics were studied at IVTAN.

The IVTAN Association divisions include a Special Design Bureau and a Pilot Production Capability. Using these capabilities, engineering and design concepts are embodied into actual products and facilities. Thus, because of the efforts of IVTAN, unique experimental installations were developed and manufactured, such as a pilot 25 MW_e power MHD installation, high-power gas-dynamic lasers for metallurgy, and numerous experimental devices. In the material divisions of IVTAN, various high temperature construction materials have been developed.

Since 1977, IVTAN has developed pulsed MHD generators based on solid rocket fuel plasma generators. The development of these devices was in Kurchatov's Atomic Energy Institute. The power sources were intended for deep electromagnetic sounding of the crust of the earth. The first use of a pulsed MHD generator was for earthquake prediction in the Pamir Mountains in Tadjikistan and later the generators were used in Tang-Shang in Kirgizia A unique Khibiny experiment was performed in which a high-power pulsed MHD generator was used as a source of electromagnetic field for a large scale deep sounding of the crust of the earth. The coast line of the Rybachii Peninsula (Kola Peninsula) served as the load for the source. Last but not least, a series of experiments was performed using the MHD generators as energy sources for oil and gas prospecting on the Pre-Caspian depression and on the Siberian platform.

Within the framework of the program, IVTAN was responsible for the following tasks:

1. IVTAN, as the principal subcontract executor, was responsible for administrative issues with its subcontractors: subcontracts negotiations and supervision of the development, manufacturing, and delivery of the facility components; obtaining the necessary licenses, permissions, and receiving authorizations for the facility development and export; selection of transportation, receipt of the necessary permissions, and facility transportation; coordination of technical documentation development, translation of the technical documentation into English; business communications; organization of the Textron team's reception in Russia as well as the Russian party subcontractor representative's mission in the United States; and general supervision and work coordination.

2. In addition, IVTAN was responsible for the following technical tasks: development of the electrical schematics in conjunction with Nizhny Novgorod of the three-channel MHD facility; development and manufacture of a highly automated control, measuring, monitoring, and recording system (CMMRS); development and manufacturing of the initial excitation system (IES); development and manufacturing of a dummy load; development of the Aerojet and Phillips

Laboratory personnel training program, participation in the training; development of the acceptance test program in Russia, participation in the test-site preparation for the tests and in the test performance; development of the acceptance test program in the United States, and participation in this test performance; and delivery of the final report.

IVTAN personnel from the Moscow headquarters and from the IVTAN Research Station in Bishkek, Kirgizia, participated in technical efforts of this program.

2.2.3 Nizhny Novgorod Machine Building Plant

The Nizhegorodsky Machinery Plant Production Association (Nizhny Novgorod) is one of the oldest machinery establishments in all of Russia. During its history, the plant repeatedly changed its field of expertise. Nevertheless, the main fields of interest for the plant have been marine vessels, locomotives, vans, steam-engines, oil processing equipment manufacturing, and weapons production: ammunition, barrel dies for guns and cannons, and cannon assembly. Nizhny Novgorod was the first plant in Russia to build an open-hearth furnace or to develop high-speed river vessels. This plant was the first one to manufacture a Soviet tank.

For several decades, Nizhny Novgorod was incorporated in the weapons industry. During World War II, the plant not only was one of the main weapons sellers (one out of every two cannons built for the Soviet Army during the war was supplied by the plant), but also enhanced its metallurgical production. After the end of World War II, the Nizhegorodsky Machinery Plant became a base for developing various new technologies and installations aimed at combined military and civilian use such as vulcanizing installations and aerial systems, while continuing efforts with renewed weapons development and production. The plant participated in the creation of wide aperture optical telescopes as well. Since 1969, the plant has been involved in the development and production of pulsed MHD generators using solid fuel plasma generators. In its Special Design Bureau, MHD installations as well as MHD channels were developed. All Russian pulsed MHD facilities were assembled here.

The wide experience of the Nizhny Novgorod personnel in the area of pulsed MHD installation development and completion predetermined its participation as a principal subcontractor in the Pamir-3U facility development and manufacturing. Its role was as follows: the facility configuration and design development; the numerical study of different operational modes, to provide preassigned values of current pulse amplitude and duration (jointly with IVTAN); MHD channel manufacturing; the facility assembly; the Electrical Equipment Unit assembly; participation in the acceptance tests in Russia and in the United States; participation in the development of technical documentation; participation in the training of Aerojet and Phillips Laboratory personnel; and participation in the final report compilation.

2.2.4 Lubertsy Research and Production Association

The Lubertsy Research and Production Association (Soyuz) is also experienced in the weapons industry. The organization specializes in prospective power facilities, rocket fuels and powders, chemical processes, and installations. Soyuz has manufactured grains and motors for geophysical, meteorological, and space rockets, gas generators, explosives for mining, oil and gas production, and building industries for many years. Soyuz also develops launch escape systems, pulsed liquid fast fire-extinguishing devices, and other high-technology equipment.

All types of powder charges used for the pulsed MHD generators as well as the plasma generator cases for the charges have been developed by Soyuz. Moreover, the charges and plasma generator cases for all of the pulsed MHD generators currently in operation have been

manufactured by Soyuz. Under the contract, Soyuz performed the following tasks: plasma generator case manufacturing; igniter and squib manufacturing and delivery; powder charge manufacturing; performance, in conjunction with IVTAN, of the random tests on the powder charges; participation in the acceptance tests in Russia and in the United States; participation in technical documentation development; participation in the training of Aerojet and Phillips Laboratory personnel; and participation in the final report compilation.

2.2.5 Geodesiya Research and Development Institute

The Geodesiya Research and Development Institute (Geodesiya), at Krasnoarmejsk near Moscow, also belongs to the weapons industry. Geodesiya, which was formed sixty years ago, specializes in techniques and means of weapons testing as follows: testing of solid fuel rocket engines, rocket units and modules, and power engines based upon hydroreacting fuels; combined testing of rocket and aviation weapons; aerodynamic testing of weapons inside aerodynamic tubes and special gas dynamic and vacuum facilities; full-scale testing (by shooting) of reactive and barrel artillery ammunition; ground stationary testing (by blasting and explosion) of fighting units of rockets, aviation bombs, and ammunition; and complete dynamic testing of weapons and ammunition systems against external vibration and shock attack.

For the test performance, Geodesiya possesses one of the largest proving grounds where well-developed, specialized test-sites, buildings, and facilities are located. All Russian pulsed MHD installations have been tested at Geodesiya. Because of its experienced personnel and sufficient equipment, as well as its location near to Moscow, this test site was chosen for the Pamir-3U acceptance tests in Russia. The Geodesiya role included: the test preparation and support and the performance of acceptance tests including the five hot-fire runs of the Pamir-3U facility; and participation in the Pamir-3U facility preparation for transportation.

2.2.6 Aerojet

Aerojet is one of the major developers, manufacturers, and operators, of solid, liquid, and hybrid rocket engines in the United States. During the last fifty years, Aerojet has been involved with a number of rocket engine development and production programs for such applications as launch vehicles, orbital vehicle maneuvering, space systems, interceptors, man-rated vehicles, and reusable engines.

Aerojet participated in the program as a subcontractor to Textron Defense Systems and was primarily involved in the Acceptance Test Program in the United States. Aerojet provided the necessary engineering, management, technical manpower, and test facilities to conduct an acceptance test program of eight Pamir-3U system tests at its Sacramento, California facilities during February, 1995. Technical and management support was also provided to assure the testing met all applicable safety, environmental, and permitting requirements at the Sacramento site. In addition, Aerojet provided support and guidance to the U.S. Air Force for acquiring the permits necessary to test at an Air Force site. Aerojet management and technical personnel also observed preliminary acceptance tests of the Pamir-3U system in Krasnoarmejsk, Russia during August, 1994 to gain firsthand information on the system operation and its testing.

2.3 PROGRAM OBJECTIVES

The objectives of the program were to deliver to the United States Air Force Phillips Laboratory a transportable, 15 MW_e MHD power system capable of performing 250 hot-fire tests over a two year period of time and a complete set of documentation to enable the Phillips Laboratory personnel to operate, maintain, service, and repair the facility and to conduct a

performance demonstration and acceptance test program. These objectives were achieved within the requirements of the program as described in Section 2.5.

The 15 MW_e transportable MHD power system objective was achieved through the use of the IVTAN Pamir-2 MHD power system hardware. This hardware was originally developed over twenty-five years ago and has been used successfully for many test programs conducted during that time. As a result of the use of existing hardware, drawings and operational and safety manuals were prepared based on the extensive hardware use and experience.

The test program objectives included a maximum power test, a nominal power test, and a maximum duration test. In addition, the performance demonstration program objectives included operation over the full resistance range of operation, all Pamir-3U operating modes, and various functional parameter settings. The overall test program objective was to fully demonstrate the overall range of operation and the flexibility of operation of the Pamir-3U MHD power system.

2.4 SCOPE

The Pamir-3U program scope was to deliver the required hardware within the constraints of the program cost and schedule. The performance of the system was optimized to achieve the necessary power requirements for the load resistances specified. The power system was optimized to fit within the system mass and volume envelope specified. Further optimization to maximize power and/or energy extraction or to minimize mass or volume beyond the contract requirements was not performed.

The program scope also included performance testing to achieve certain power and operating levels. An overall test program to optimize performance at all operating conditions was not performed. The overall design scope included the use of as much technology from previous Pamir series hardware programs as possible. This approach was selected to minimize the cost, schedule, and performance risk of the program.

2.5 REQUIREMENTS

The program requirements included both performance and schedule goals. The program schedule required the design, fabrication, assembly, and test program to be completed within two years. The fraction of time allocated to each activity within the entire time period was not constrained by program requirements. The program culminated with the delivery of the Pamir-3U MHD power system to the U. S. Air Force Phillips Laboratory.

The specific technical requirements of the program are listed in Table 2. These items define the technical requirements of the MHD power system and determine the type of subsystems necessary to achieve the program requirements. In addition to the specific technical requirements listed, the MHD power system must be capable of transportable operation and test operation at a remote test site. This includes an implicit requirement for easy set-up and installation and rapid disassembly and movement to another test site. Requirements for remote test site operation require a stand alone control system and data acquisition system to monitor the test results, which are included as a part of the Pamir-3U MHD Power System.

TABLE 2
MHD POWER SYSTEM TECHNICAL REQUIREMENTS

Parameter		Value
Maximum Net Power Output		15 MW_e
Maximum Operating Duration		10 s
Operating Duration Range		2 to 10 s
Maximum Mass		18,000 kg
Volume Restrictions:	Length	10 m
	Width	2.4 m
	Height	2.4 m
Electrical Load		20 ± 5 mΩ
Number of Tests		250 shots
Mean Time Between System Failures		30 days or 20 shots
Mean Time Between Subsystem Failures		60 days or 40 shots

3.0 DESIGN AND DESCRIPTION OF HARDWARE

3.1 POWER UNIT

The Pamir-3U power unit IM1-3.01.00.000 is designed for conversion of kinetic and thermal energies of the ionized flow of propellant combustion products in the magnetic field to electrical energy. The main power unit components are shown in Figure 5. These components are: plasma generators with MHD channels and stops (1), a magnet system (2), frame (3 and 4), shields (5), stops (6), supports (7), buses (8), strapping tapes (9), base plate (10), and plate (11). An overview of the facility installation is shown in Figure 6.

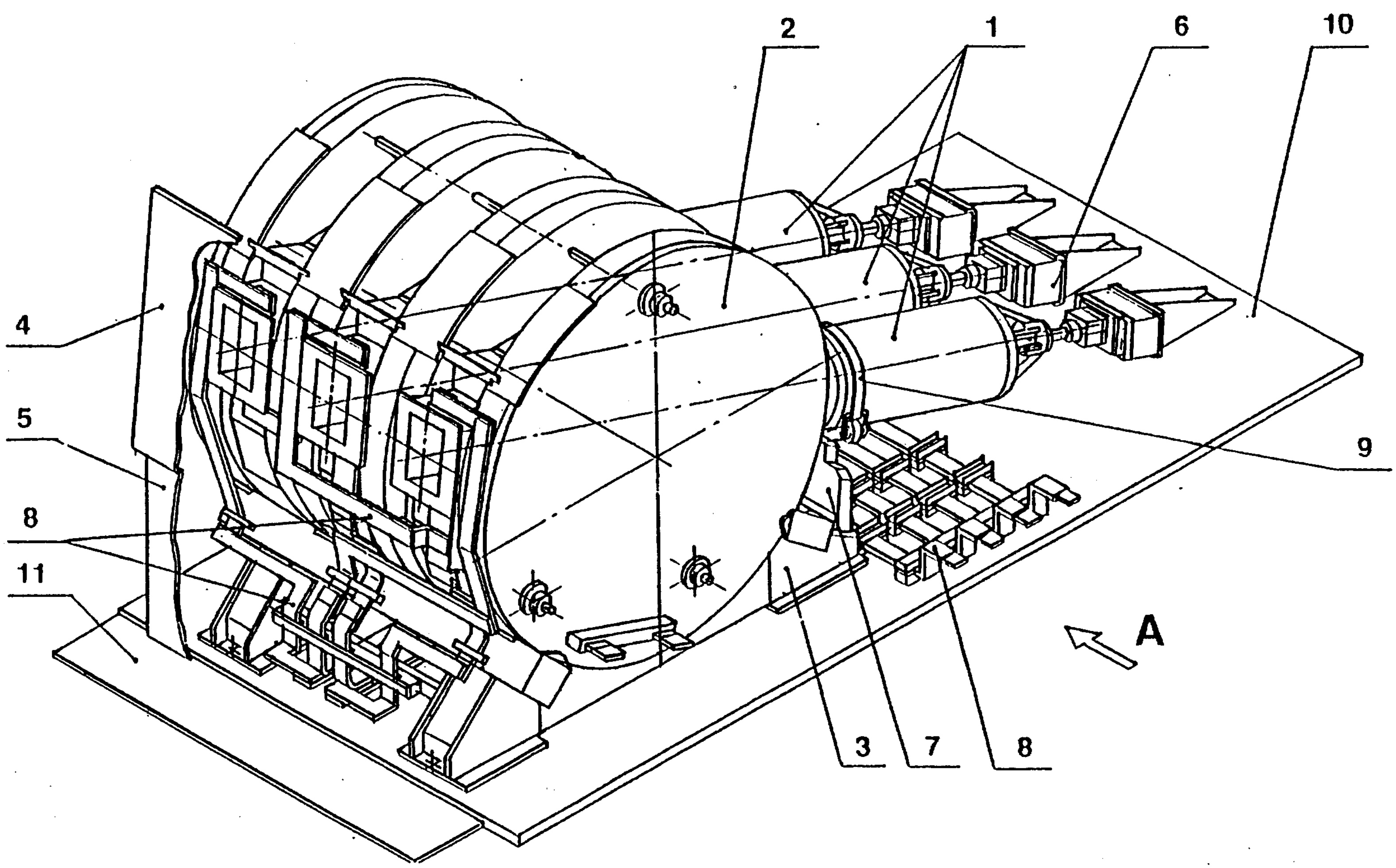
The magnet system is installed on a frame that is attached by four anchor bolts on the base plate. The MHD channels are placed between four electrical magnets of the magnet system. The longitudinal axes of the MHD channels are inclined at an angle of 19 degrees to the horizontal. The working section centers of the MHD channels are coaxial with the magnet system. The plasma generators rest on supports and are attached to them by a yoke with a metal band.

The reactive force arising from operation of the plasma generators is contained by the stops attached to the base plate. For this purpose, four holes of 26 mm diameter are provided in each stop. For electrical isolation and prevention of current leakage across the electrical circuit, which contains the electrodes of the MHD channel, the propellant combustion products, the front heads of the plasma generators, the propellant combustion products, and the back heads of the plasma generators, there are mineral fiberglass reinforced plastic insulated plates and isolation blocks made from the same material.

The shields (4 and 5) and the plate (11) are used for protection of the power unit components and embedded parts of the test site against the heating action of the high temperature flow of combustion products. The shields (4) are attached to the MHD channel flanges; the shield (5) is attached to frame; and the base plate (10) is located on the surface of the embedded parts of the test site. These arrangements are shown in Figure 7. The shield attachments are made with standard fasteners. The material of the shields and the plate is a mineral glass-reinforced plastic of 12 mm thickness. Figure 8 shows the shields installed.

The electrical assembly is made by flat copper buses (8), which are shown in Figure 5. The bus cross-sections are 100 mm x 10 mm and 80 mm x 100 mm. The buses with a direct operating voltage of 2.5 kV are insulated from the power unit components, which are grounded. For the purpose of decreasing the contact resistance, a tin coating with a nickel precoat is applied to the bus contact surfaces. The bus connections are made by standard fasteners.

The mass of the power unit with the charged plasma generators is 12,700 kg. The overall dimensions of the power unit are a length of 4500 mm, a width of 2000 mm, and a height of 2080 mm.



1 - PLASMA GENERATOR WITH MHD CHANNEL AND STOP; 2 - MAGNET SYSTEM; 3 - FRAME; 4,5 - SHIELDS; 6 - SUPPORT; 8 - BUSES; 9 - STRAP; 10 - BASE PLATE; 11 - PLATE

P7552

Figure 5 Pamir-3U System Power Unit

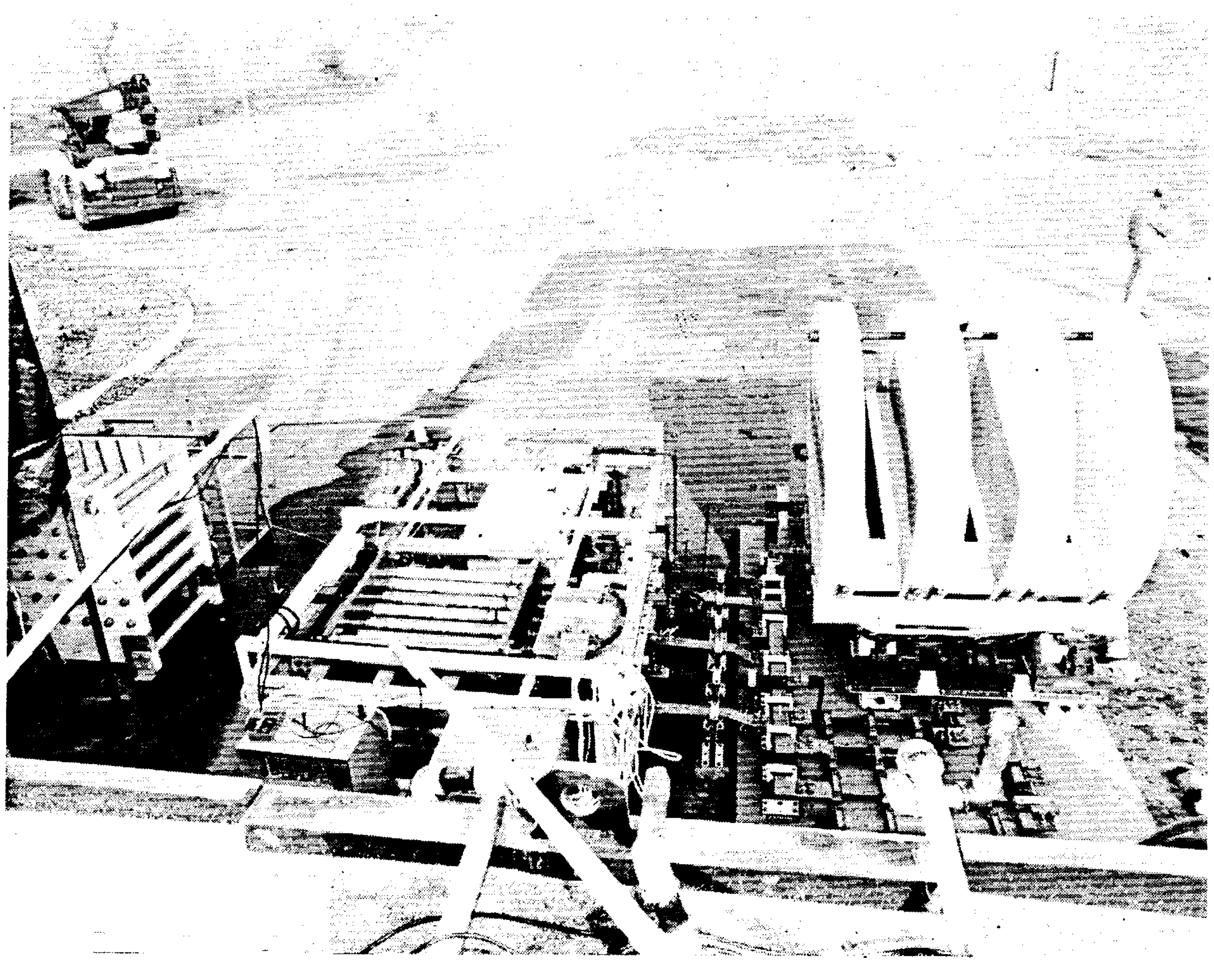


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Figure 6 Overview of the Pamir-3U MHD Installation

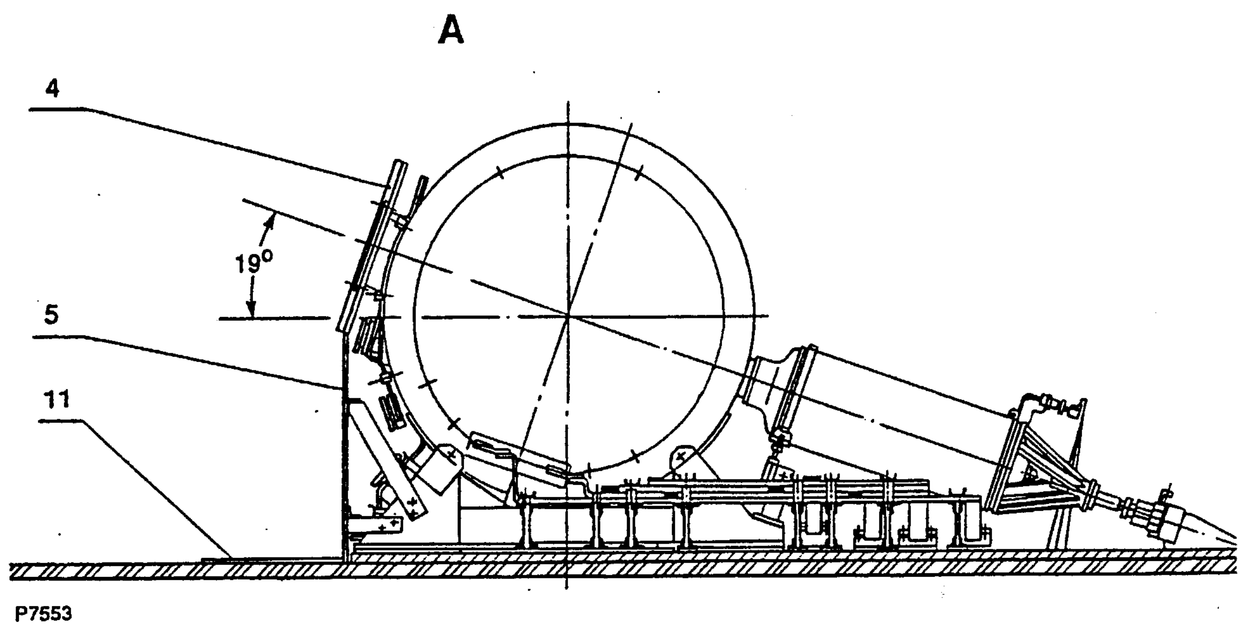
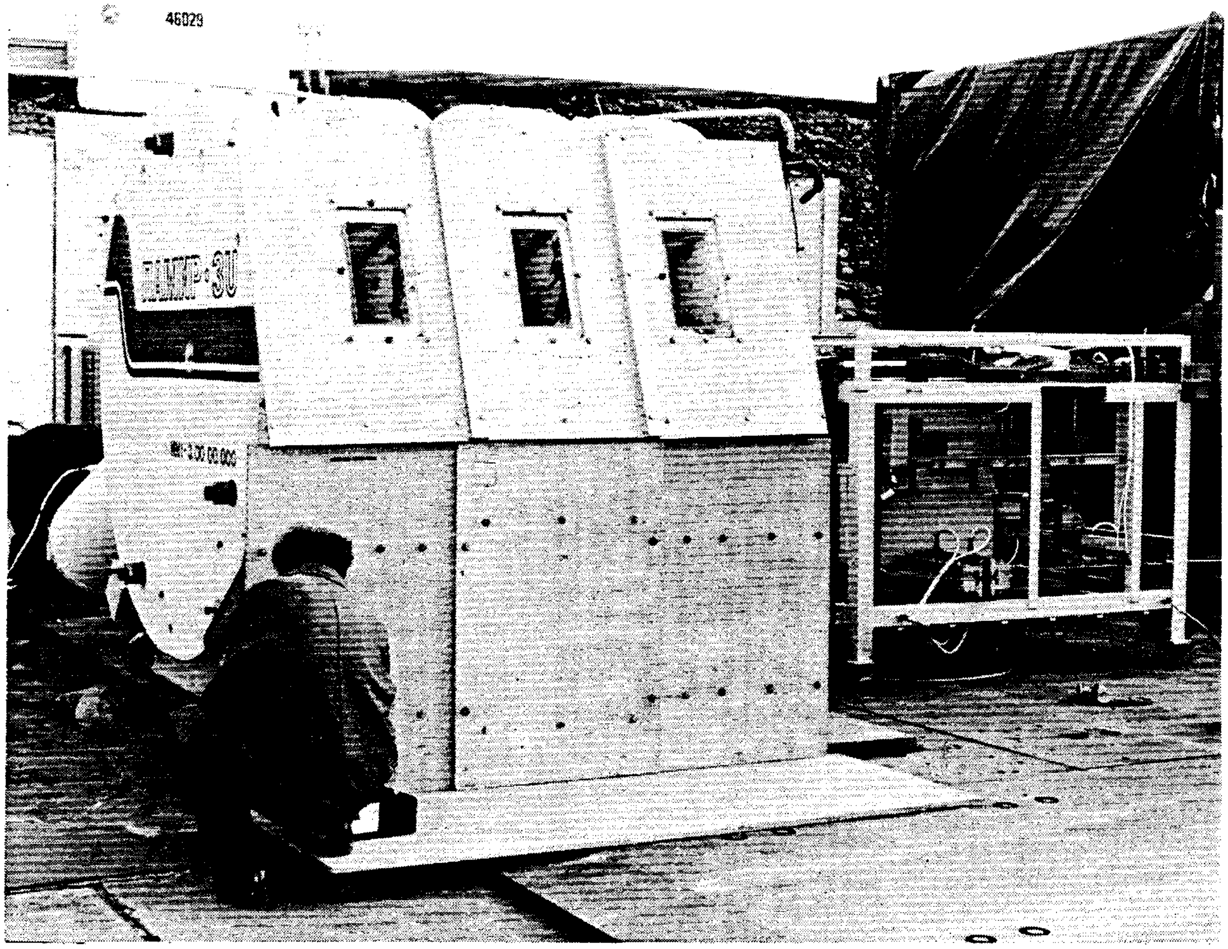


Figure 7 Pamir-3U MHD System Power Unit - Elevation View



P7583

Figure 8 Pamir-3U MHD System with the Protective Shields Installed

3.1.1 Plasma Generator

The GP77 plasma generator is designed for operation as a part of the Pamir-3U MHD system. Technical data for the plasma generators is given below:

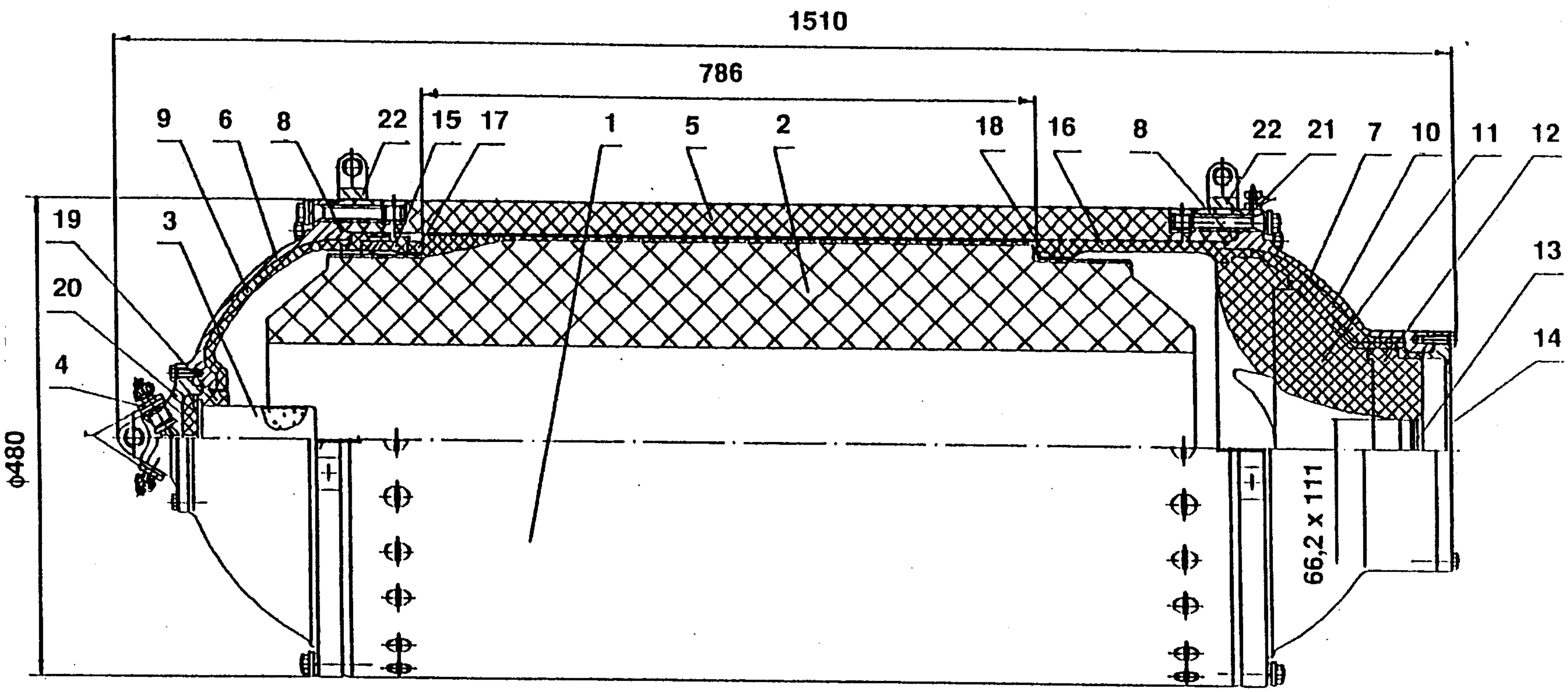
- mass flow rate of combustion products	18.5 to 26.0 kg/s
- operation time	7.4 to 10.5 s
- combustion pressure (steady state)	3.4 to 5.2 MPa
- time of grain ignition and achievement of operating conditions (up to P_c =0.8 P_a, where P_c = actual combustor pressure and P_a = average combustor pressure)	< 0.1 s
- nominal area of the throat	73.46 cm^2
- mass of solid plasma-generating propellant	200 kg
- mass of loaded plasma generator	400 kg
- permissible charge temperature operating range	5 to 35 °C
- temperature range for storage and transportation	-40 to + 40 °C

The variations of the plasma generator parameters - mass flow rate, operation time, and combustion pressure - are caused by variations of the burning rate of the propellant as well as by the dependence of the burning rate on the initial charge temperature. In addition, operation outside of the permissible charge temperature operating range may be allowed if certain provisions are satisfied. For the operation of the MHD power system in the mode of maximum pulse duration according to the technical requirements, the special modification of the plasma generator with the initial charge temperature of 0°C and an enlarged throat area of 80 cm^2 was analyzed and approved for operation with the plasma generator charges used for the acceptance test program. Similarly, a separate analysis was developed and subsequently approved for operation at 40°C for the plasma generator charges used for the acceptance tests. This analysis, which results in the approval of only the plasma charge batch being studied, is based on archival data of previous batches, mechanical and chemical data of the batch of interest, and actual performance data of the batch during operation. If the appropriate criteria are satisfied, permission to operate at initial charge temperatures outside of the range of 5 to 35°C may be given.

The GP77 plasma generator consists of the following main units: GP77-01 generator case; OE72 plasma-generating solid propellant charge; DE91 igniter; and two UDP2-3 squibs. The design of the plasma generator is shown in Figure 9. The plasma generator is made of a load-bearing case (1) that is a combustion chamber where the solid propellant charge (2), the igniter (3), and the squibs (4) are located. A photograph of the charge inserted into the case is shown in Figure 10.

The load-bearing generator case consists of a fiberglass plastic pipe (5) to which the front head (6) and back head (7) are attached with pins and bolts. Rubber rings (8) provide leak-proof joints between the pipe and the heads. The front and back heads are made of high strength steel and have a welded construction of spherical stamped parts and flanges.

The heads are protected by heat-proof coatings (9 and 10) on the inside surface. The inserts (11) are made of four graphite sectors. High strength graphite inserts (12) are installed inside the back head with the help of thermostable adhesive. The insert has a rectangular outlet that is the nozzle throat of the plasma generator. A membrane (13) is placed in the nozzle outlet for sealing of the nozzle throat. The joints between the back head and MHD channel are covered by a safety lift-off cover (14).



1-CASE, 2-CHARGE, 3-IGNITER, 4-SQUIBS, 5-PIPE, 6-FRONT HEAD, 7-BACK HEAD, 8-RING, 9,10-HEAT-PROOF COATINGS, 11-INSERT, 12-INSERT, 13-MEMBRANE, 14-COVER, 15-FRONT SUPPORT, 16-BACK SUPPORT, 17,18-WASHER, 19-SLEEVE, 20-COVER, 21-UNION, 22-BRACKET.

P7563

Figure 9 GP77 Plasma Generator

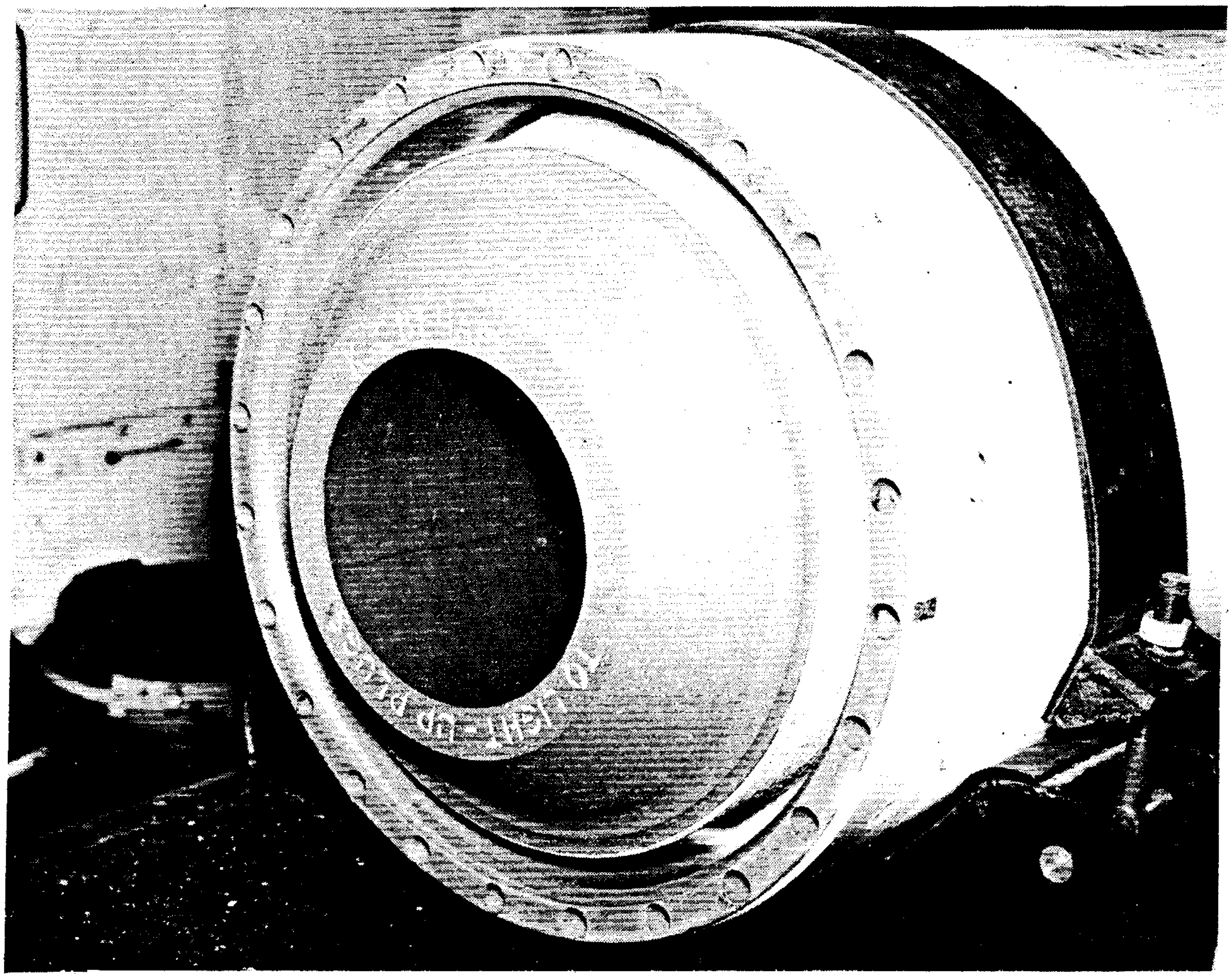


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Figure 10 Plasma Charge Inserted into the Generator Case

In the case, an OE72 solid plasma-generating propellant charge is retained by two supports: front (15) and back (16), which have rubber washers (17 and 18). The rubber washer (18) seals the joint on the support surface of the charge which prevents the penetration of combustion products along the cylindrical gap between the fiberglass plastic pipe and the external surface of the charge. The OE72 charge is made of a single construction, is inhibited on the external cylindrical surface, and has end and internal surface burning. The DE91 igniter is mounted in a plastic sleeve (19) and covered by a cover (20), which has two threaded holes for UDP2-3 squibs. The squibs are shown in Figure 11 on the left, and the igniter is shown on the right. The unions (21) for mounting pressure indicators that measure pressure in the combustion chamber of the plasma generator are located on the flanges of the front and back heads. There are two brackets (22) on the generator case for lifting. The generator is ignited by a current pulse that is transferred to the squibs. The operating current is 1.5 ± 0.003 A in each bridge.

The warranty period is four years for the GP77.01-0 generator case, three years for the OE72 charge, including one year in field conditions, ten years for the DE91 igniters in hermetically sealed packages, and ten years for the squibs in hermetically sealed packages.

3.1.2 MHD Channel IM112-5.00.000

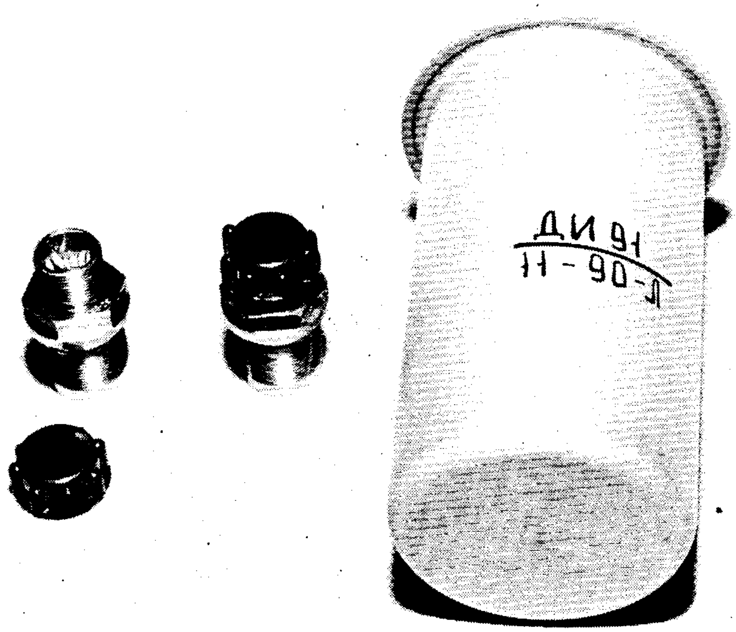
The MHD channel is intended for operation as a part of the Pamir-3U MHD facility. The principle of operation consists of the acceleration of the propellant combustion products to supersonic flow through a gas dynamic expansion, interaction of the flow with a magnetic field, and exhaust of combustion products into the atmosphere. During the interaction of the ionized gas flow with the magnetic field, the electromotive force between opposite electrodes of the MHD channel is induced by the connection of a load to the electrodes, which results in an electric current flowing between the electrodes. In so doing, a conversion of kinetic and thermal energy of the combustion products to electrical energy occurs. The MHD channel can be operated at an ambient temperature from - 30°C to + 40°C and at an air relative humidity up to 95% at a temperature of + 25°C. For ambient temperatures below -30°C, the channel epoxy resin loses its mechanical strength, which is a critical area for maintaining channel integrity. This requirement is based on the calculated strength properties for the data available. For temperatures above 40°C, no data has been readily available, and there has also been no need to consider operation in this temperature range.

3.1.2.1 Technical Parameters

The general technical parameters are listed in Table 3.

TABLE 3
MHD CHANNEL TECHNICAL PARAMETERS

Parameter	Value
Working volume	0.033 m^3
Insulating wall thickness	42.5 mm
Electrode wall thickness	56.0 mm
Mass	197.0 kg
Insulation resistance	4.0 MΩ
Direct voltage during check-out of electric insulation strength (allowable leakage current not more than 5 mA)	10.0 kV
Maximum pressure in the working area	0.85 MPa
Maximum electrode current density	20.0 A/cm^2



P7588

Figure 11 UDP2-3 Squibs and DE91 Igniters

3.1.2.2 MHD Channel Conception and Design

The IM112-5 MHD channel, shown in Figure 12, is a Faraday type channel with continuous electrodes. The following factors act along the MHD channel gas dynamic path: supersonic flow of high temperature combustion products containing up to 40% of condensed phase (Al_2O_3); strong braking of the gas flow by the magnetic field interaction that is accompanied by the occurrence of shock waves and a pressure increase in the working area up to 0.85 MPa; and the arc nature of the electric current flow at the plasma - electrode boundary by a current density up to 20 A/cm^2. In this application, the MHD channel is one of the most stressed components of the MHD facility. A photograph of two of the channels is shown in Figure 13.

The MHD channel consists of three areas: inlet, power producing zone, and outlet, which are shown in Figure 12a. In the inlet area, the combustion products are accelerated up to a Mach number of 2.4. In the power producing zone, the MHD power conversion occurs. The outlet area is intended for exhaust of combustion products and protection of the magnet system from the heat load of the gas flow.

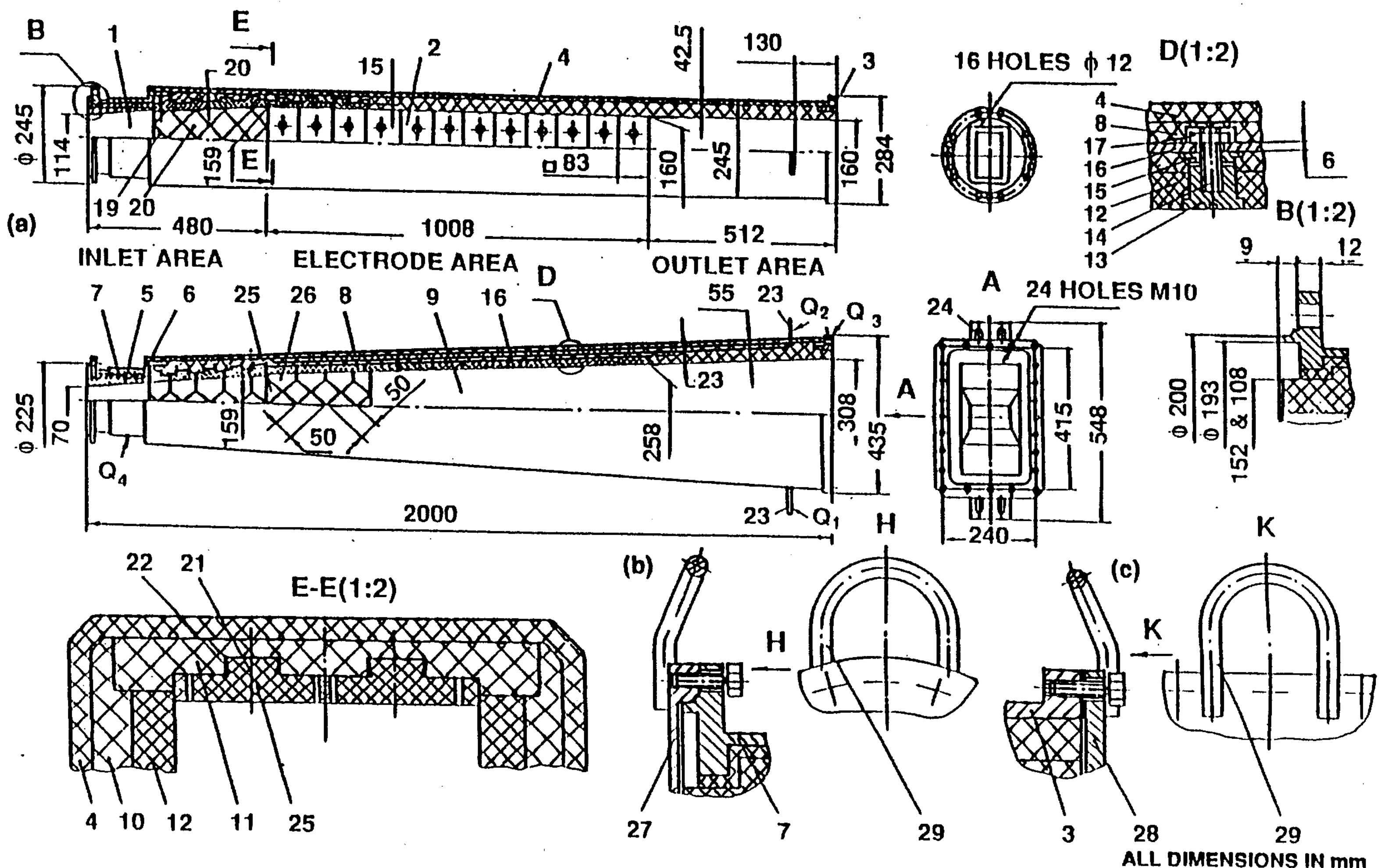
The quest for the attainment of the maximum ratio of the plasma volume to the structure volume of the MHD channel walls in the working zone imposes some restrictions on the thickness of the electrode and insulating walls. Because of the use of flat coils in the magnet system, the most important factor is the attainment of the minimum thickness of the insulating wall, which is equal to 42.5 mm.

3.1.2.2.1 Heat Protection and Erosion Resistance of the MHD Channel

The MHD channel is a heat sink unit. The heat protection is achieved through heat absorption by the design components that are made from heat-absorbing materials - ceramics and mineral fiberglass reinforced plastic.

The impact of the high temperature gas flow and the current density distribution results in an electric intensity change along the channel length. For the purpose of providing the same resistance of the MHD channel components and for decreasing the MHD channel cost, different materials are used for the interior surfaces of the channel walls. At the MHD channel inlet, where the electric intensity is a minimum and the heat flow is a maximum, the lining is made of an expanded insert of erosion resistant graphite. In the pre-electrode area and at the beginning of the power producing zone of the insulating walls, where the electric intensity is a maximum and the heat flow is less, the lining is made of modules of a high temperature, electrically insulating ceramic. The modules are plates having a different shape.

For the purpose of decreasing the erosion at the boundaries of the adjacent modules, the intermodule clearances are located not in parallel, but at an angle of 45 or 90 degrees to the gas flow direction. The gas side lining on the insulating walls of the working zone, excluding the inlet part of the working zone, on the insulating walls of the outlet area, and on the outlet area of the electrode walls is made of panels of a high temperature, electrically insulating, mineral fiberglass reinforced plastic.



A) MHD CHANNEL; B) TRANSPORT END CAP ON A FRONT FLANGE; C) TRANSPORT END CAP ON A BACK FLANGE.
1 - INLET INSERT WITH A FLANGE; 2 - DUCT; 3 - BACK FLANGE; 4 - LOAD BEARING SHELL; 5 - GRAPHITE INSERT; 6 - HEAT PROTECTION; 7 - FRONT FLANGE; 8 - ELECTRODE WALL; 9 - INSULATING WALL; 10, 11 - CASE PARTS OF ELECTRODE AND INSULATING WALLS ACCORDINGLY; 12 - ELECTRODE; 13 - BUSHING; 14 - STUD BOLT; 15 - NUT; 16 - CURRENT PICK-OFF BUS; 17 - NUT; 18 -COVER; 19, 20 - CERAMIC MODULES; 21 - MODULE TAIL; 22 - SEAT FOR TAIL; 23 - CURRENT LEAD; 24 - GROOVE; 25, 26 - CERAMIC MODULES; 27,28 - TRANSPORT END CAPS; 29 - SHACKL

P7554

Figure 12 MHD Channel Arrangement

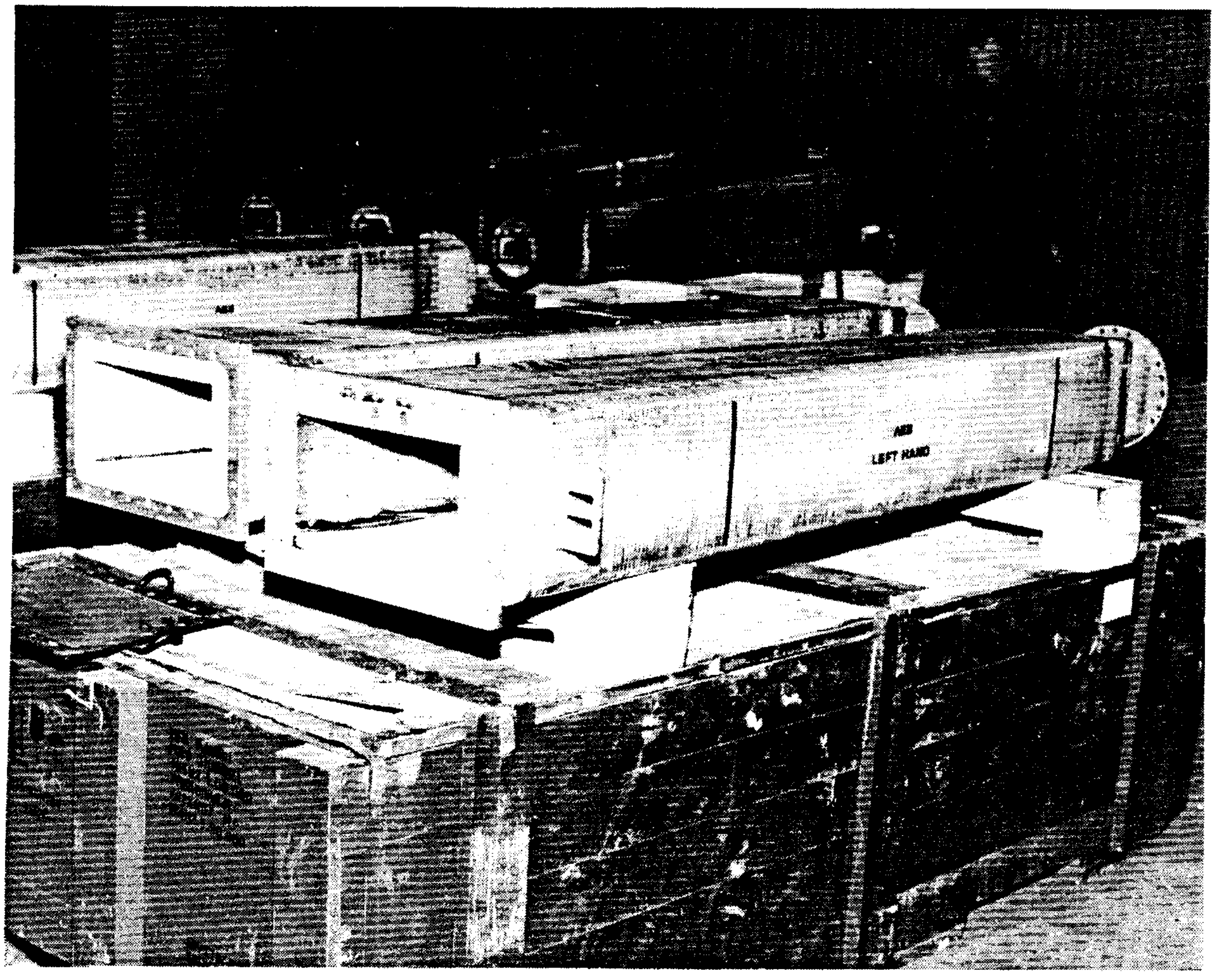


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Figure 13 MHD Channels

3.1.2.2.2 Electrodes and Current Taps

The large experience of the development of the pulsed MHD facilities has shown that the most suitable material for the MHD channel electrodes is a dense, arc-resistive graphite. This material provides acceptable near electrode voltage drops and erosion resistance without cooling during the normal operating time of 10 s. The electrodes are made as square plates with dimensions of 83 mm x 83 mm. Each electrode is attached to the electrode wall at one point. The 24 electrodes are installed on the electrode wall. The electrodes are connected by a copper current tap attached to the bus.

The current leads are located at the MHD channel outlet. They provide for the resistance to the action of the electrodynamic forces, $F = J \times B$, where J is the current in the power take-off bus and B is the magnetic induction in the MHD channel working volume.

3.1.2.2.3 Electrical Insulation

The electrical insulation of the electrodes located on opposite walls along the hot gas surfaces is made in the pre-electrode area and at the beginning of the working area by application of a high temperature, electrically insulating mineral fiberglass reinforced plastic.

A volume of electrical insulation is obtained by the manufacture of the case parts of the electrode and insulating walls from plates of mineral fiberglass reinforced plastic, and by the manufacture of the load bearing shell from a winding of fiber-glass braid.

3.1.2.3 MHD Channel Design Description

Figure 12 illustrates the four parts of the MHD Channel: inlet insert with a flange (1); duct (2); end flange (3); and load bearing shell (4).

The inlet insert with the flange consists of a graphite insert (5) with a rectangular cross-section with a heat-protective coating (6) applied to its surface, and a steel flange (7). The duct is formed by two electrode walls (8) and two insulating walls (9). The case parts (10 and 11) of the electrode and insulating walls are made from a high temperature, glass-reinforced plastic.

The twenty-four graphite electrodes (12) are attached to the electrode wall case by bushings (13) of a high temperature alloy, by steel studs (14), and nuts (15). A copper power take-off bus (16) is connected to the nuts (15) and tightened with nuts (17). The bus is covered by a fabric-based laminate cover (18). The hot gas surface of the inlet area of the electrode wall is formed by ceramic modules (19 and 20). The modules are plates having tails with a back cone. The tail is installed into a seat (22) on the case wall. The current take-off bus has a current lead (23) with grooves (24) for connection to the magnet system and a load.

A hot gas surface of the pre-electrode area and the beginning of the working area of the insulating wall is formed by ceramic modules (25 and 26). The attachment of the ceramic modules to the case is similar to the attachment of the modules on the electrode wall. The electrode and insulating walls are connected together by a high temperature adhesive.

A load bearing shell (4), which reacts the gas dynamic and electrodynamic forces, is applied to the duct (2) with flanges (4 and 7) by a winding of fiberglass braid. The necessary gas leak integrity of the MHD channel is ensured by the following procedures: a) connection of the electrode and insulating walls by a high temperature adhesive with a mineral base; b) installation of the front and back flanges with a high temperature sealing compound; c) installation of a gas-impermeable cloth on the longitudinal joints between the walls by application of an epoxy adhesive;

d) impregnation of the fiberglass braid during the winding with an epoxy compound followed by polymerization under pressure; and e) filling the clearances at the outlet of current leads with an epoxy resin-based compound.

The channel front flange is used for the assembly with a plasma generator. The channel back flange is used to connect the shield that protects the magnet system from the heat of the exhaust flow.

During transportation, the MHD channel is closed by end-caps (27 and 28), which are attached to the front (7) and back flanges (3) by bolts. This assembly is shown in Figure 12b and 12c. The end-caps have shackles made from a steel rod for lifting.

3.1.2.4 Marking and Sealing

Any markings on the MHD channel are applied to its external surface. The marking signs are: index, designation and Manufacturer's number of the MHD channel; and *Top*, *Bottom*, *Right*, and *Left* signs, needed for mounting and repair procedures. The location and length of the channel working area are labeled with marks applied to the right and left sides. The MHD channel is sealed with a lead tamper seal and a steel wire.

3.1.2.5 Container

A wooden crate is provided for the packing of the MHD channels. In each crate, two MHD channels are packed. The crate consists of two side and two face walls, a bottom, and a cover manufactured from softwood lumber. The crate is assembled with nails. On the crate bottom, two beds, on which the packed channels are laid, are installed. The channels are fixed on the bottom and the faces with additional bars. The internal surface of the crate is covered with asphalt roofing paper. The cover is covered on the outside with prepared roofing paper.

3.1.3 Magnet System

The IM1-3.01.10.000 magnet system is intended for magnetic field generation in the MHD channel working volumes. The magnet system principal views are shown in Figure 14. The magnet system consists of four round electromagnets: one left electromagnet (1), two middle electromagnets (2 and 3), and one right electromagnet (4), which are separated by glass-reinforced plastic inserts (5 and 6), and tightened by three studs (7), and protected from the exhaust gases by shields (9). The right and the left electromagnets each consist of a single electromagnet and cover, and the middle electromagnets, which differ from each other by the commutation of the current buses, consist of two single electromagnets. The single electromagnet, which is shown in Figure 15, is made from two ellipsoid flat coils (3), two outer inserts (2 and 5), and one inner insert (4), fastened by a round force binding (1), which is made of glass-reinforced plastic. Each section is wound by a copper bus with a cross-section of 16 mm x 25 mm, in two layers of 16 turns in each layer. The magnet assembly is shown in Figure 16.

For the convenience of the MHD channel installations, the upper inserts (6), shown in Figure 14, are demountable, and the lower inserts are fixed to the middle electromagnets (2 and 3), and the right electromagnet (4). Commutating buses (8) are mounted in the lower part of the magnet system and brought out through the insert windows of the single electromagnet.

On the outer surfaces of the electromagnets, the shields (9), which protect against heating from the combustion product exhaust flow are installed. The shields are made of 2 mm thick stainless steel.

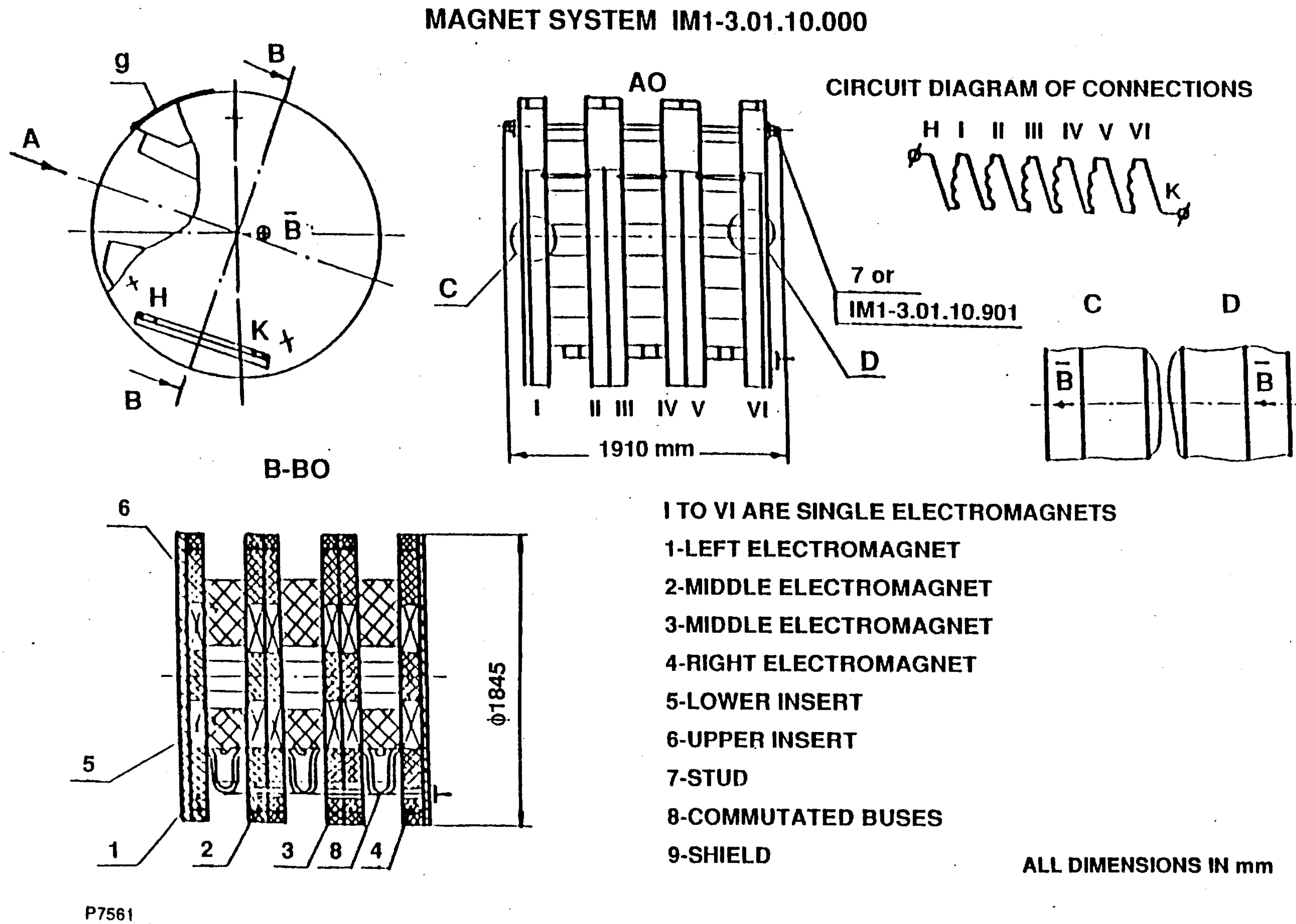
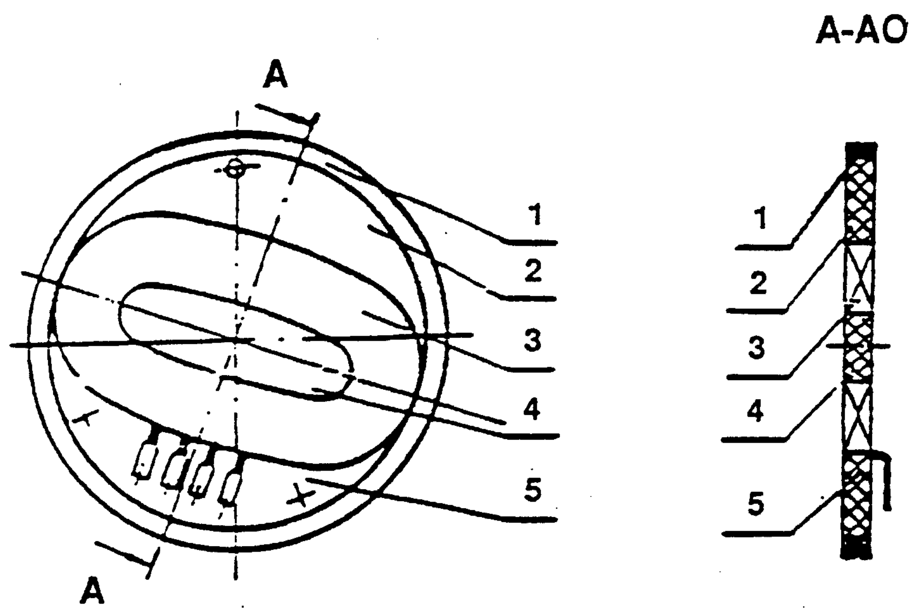


Figure 14 Pamir-3U Magnet System



1-BANDING

2-INSERT

3-COIL

4-INSERT

5-INSERT

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Figure 15 Electromagnet Assembly

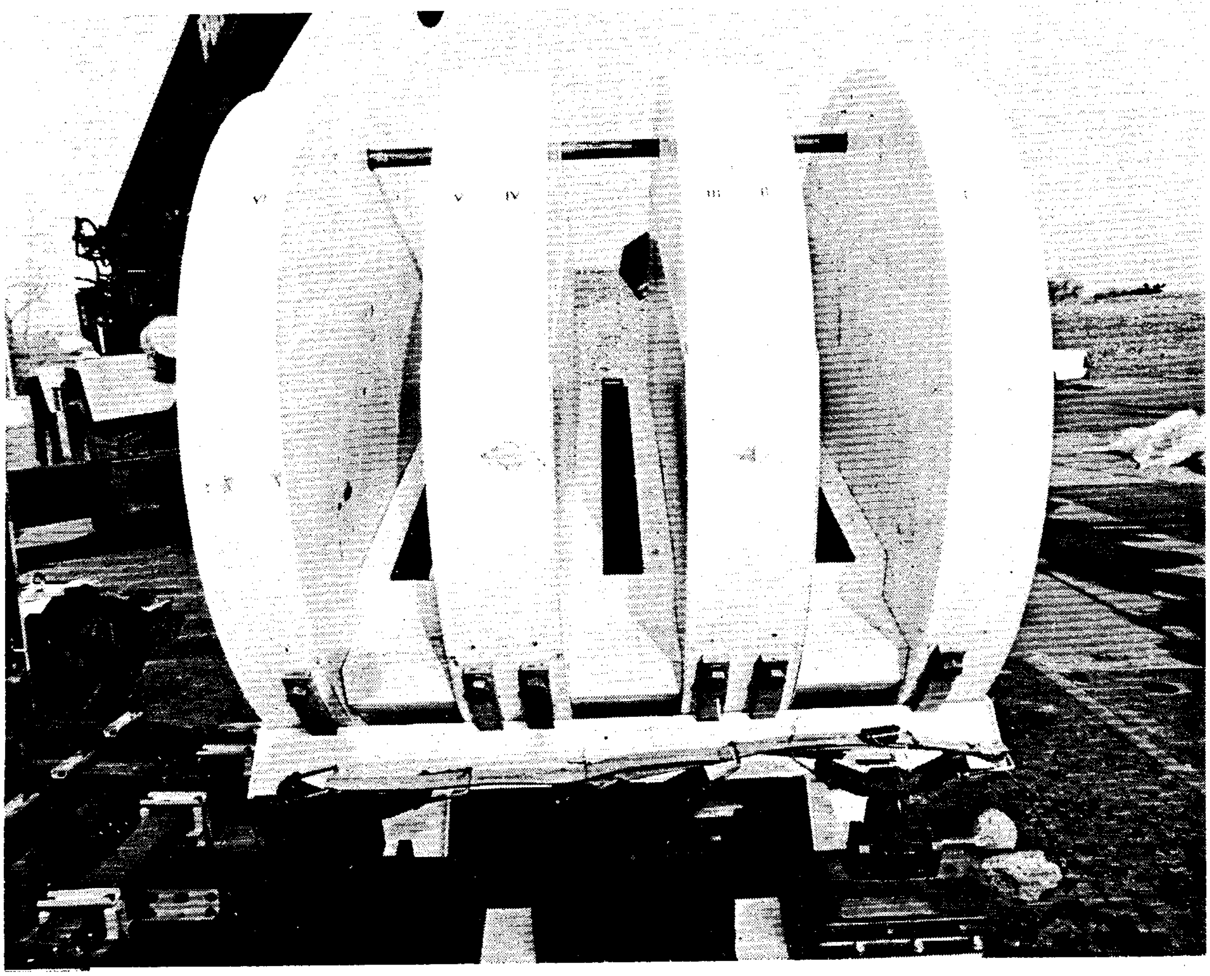

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Figure 16 Magnet Assembly

During loading and installation of the magnet system, a stud IM1-3.01.10.901, which is installed instead of the upper stud (7), shown in Figure 14, is used. The stud IM1-3.01.10.901 is made of a high-strength alloyed steel and was supplied in the Spare Parts, Tools and Accessories Set.

The electric diagram of the electromagnet connections is provided in Figure 14. The main technical parameters of the magnet system are listed in Table 4.

TABLE 4
MAGNET TECHNICAL PARAMETERS

Parameter	Value
Rated coil current	14 ± 2 kA
Limiting current for the system	20 kA
Electrical resistance	56 mΩ
Inductance	52.4 mH
Number of turns in the coil	64
Mass of the system	9600 kg

3.1.4 Plasma Generator with MHD Channel and Stop

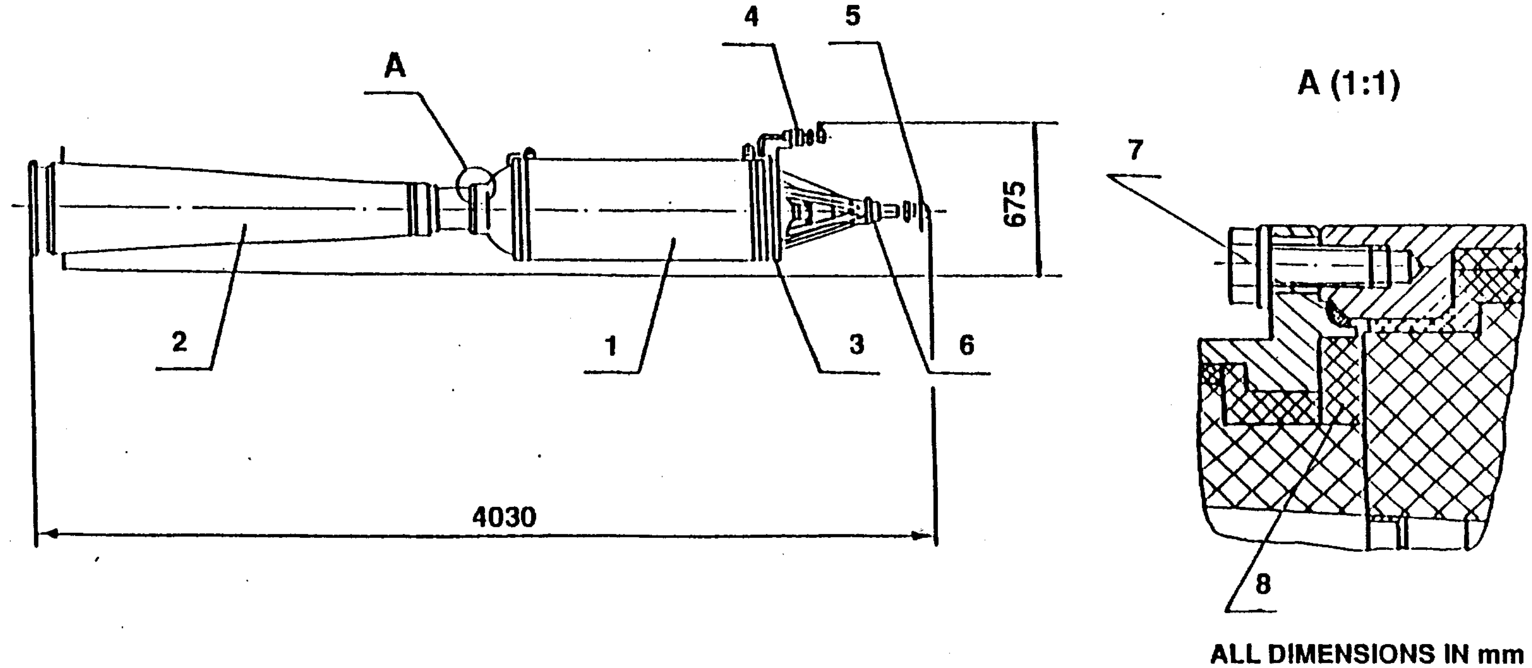
Figure 17 shows the plasma generator with the MHD channel and the stop, IM1-3.01.00.090, which consists of: plasma generator (1); MHD channel (2); cone (3); measuring unit (4); screw (5); lock-nut (6); and gaskets (7 and 8). The connection of the indicated components is made by standard fasteners. The reactive force from the plasma generator operation is transmitted through the cones and screws to the power unit stops, which are shown in Figure 5. The cone consists of a supporting flange on the plasma generator front head, a nut with buttress thread, and four bracing struts. The flange and nut are connected together by welded bracing struts. The screw is screwed into the cone nut that allows for adjustment of the MHD channel position in the magnet system. The screw is held in place by a lock-nut. The gaskets, which ensure that the connections are pressure-tight, are installed between the plasma generator and the MHD channel flanges. The assembled unit IM1-3.01.00.090 mass is 626 kg.

3.2 ELECTRICAL EQUIPMENT UNIT

The electrical equipment unit IM1-3.02.00.000 contains the commutating and measuring equipment necessary for the facility operation. The electrical equipment unit, which is shown in Figure 18, is a part of the MHD Power System, and consists of a framework (1), ballast resistance (2), protection unit (3), shunt units (4, 5, and 6), final-control rack (7), breakers (8), contactors (9), and measuring rack (10). All units enumerated above are mounted on the framework. The framework is made from steel angles and channels, and has connections for hoisting devices as well as terminals for the connection of grounding cables. The inside-unit mount is made of plain copper buses, which are installed and fixed on the Steklo-Textolyte™ (trademark for fiberglass laminate composite) support. Lengthwise, the buses have detachable joints with contact surfaces having a nickel precoat and a tin coating.

Protection of the electrical equipment unit against atmospheric precipitation is provided for by a canvas bag that is attached to the unit framework. Paint work is applied to the surface of the framework for protection against corrosion. The shunt units, the final-control rack and the measuring racks, which are installed in the electrical equipment unit, are incorporated functionally into the CMMRS. The unit mass is 1950 kg.

PLASMA GENERATOR WITH MHD CHANNEL AND STOP IM1-3.01.00.090



1-PLASMA GENERATOR; 2-MHD CHANNEL; 3-CONE; 4-MEASURING UNIT; 5-SCREW; 6-LOCK-NUT; 7.8-GASKETS

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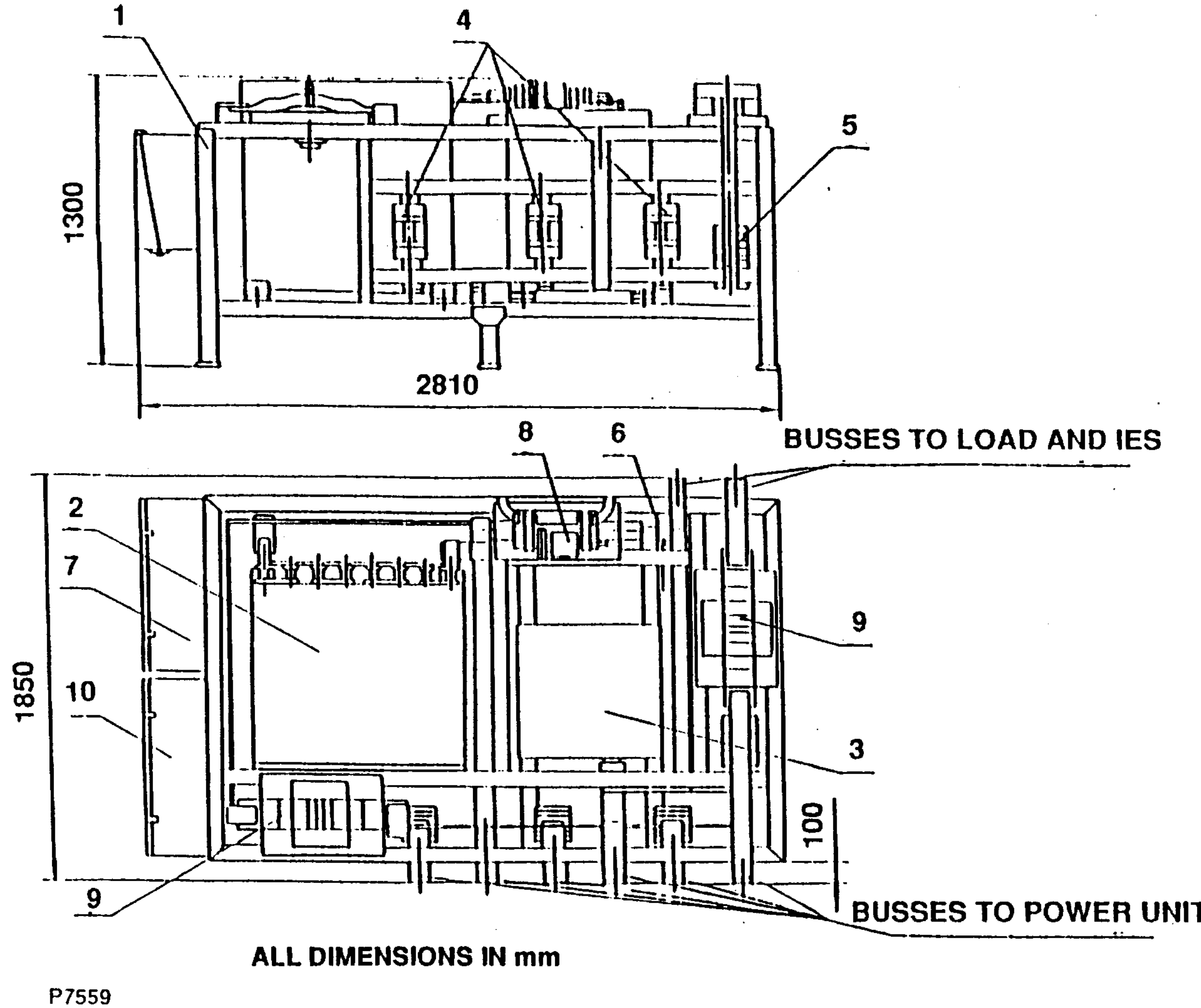
Figure 17 Plasma Generator with MHD Channel and Stop

ELECTRICAL EQUIPMENT UNIT IM1-3.02.00.000



1-FRAME WORK;
2-BALLAST RESISTANCE;
3-PROTECTION UNIT;
4-SHUNT UNIT (TM, TK1, TK2);
5-SHUNT UNIT (TH);
6-SHUNT UNIT (THB);
7-CONTROL UNIT;
8-BREAKER;
9-CONTACTOR;
10-MEASURING UNIT;

Figure 18 Electrical Equipment Unit

3.2.1 Breaker IM-115VP-1.00.000

The breaker is an explosive commutating device and is used for high direct-current, high voltage circuit breaking by an outer control signal, which is fed to its actuating parts. The breaker principal view is given in Figure 19. The breaker components are a frame, a commutator, and a jumper (15). A photograph of the breaker is shown in Figure 20.

The frame consists of a Steklo-Textolyte™ base on which two brackets (2) are installed, which serve as the breaker leads and the location for the installation of the commutator and the jumper. The commutator and the jumper are fixed by straps (3) and nuts (19).

The commutator consists of a conductor, an inner insulator (6) made from fluoroplastic, and a steel case (7) which is fixed on the conductor through the inner insulator by a nut (5). On the outside of the nut, the Steklo-Textolyte™ outer insulator (4) is installed.

The conductor consists of a bushing (8) made of aluminum alloy, a casing (12), a casing cap (14), and a paraffin cup (9). The crushed conductor element is a bushing having transverse cuts in its middle. The paraffin cup is inserted into the bushing, and the electric blasting caps (10) are inserted into the holes of the paraffin cups. The electric blasting cap wires are brought to the terminals (18) through a tube (11) the casing (12), and the casing cap (14).

The jumper (15) is a Steklo-Textolyte™ bar with a hole along the axis for the location of a wire (16). The replaceable, flexible PVC pipe (20) is inserted into the hole to protect the hole surface from vapor metallization of the explosion of the wire (16) during the breaker operation. The jumper ends terminate with metal lugs having a thread for screwing the coupling nut (17) on the attached gas vent pipes (13). The gas vent pipes can be rotated about the jumper axis so that the exhaust of the wire explosion products is directed in a safe direction.

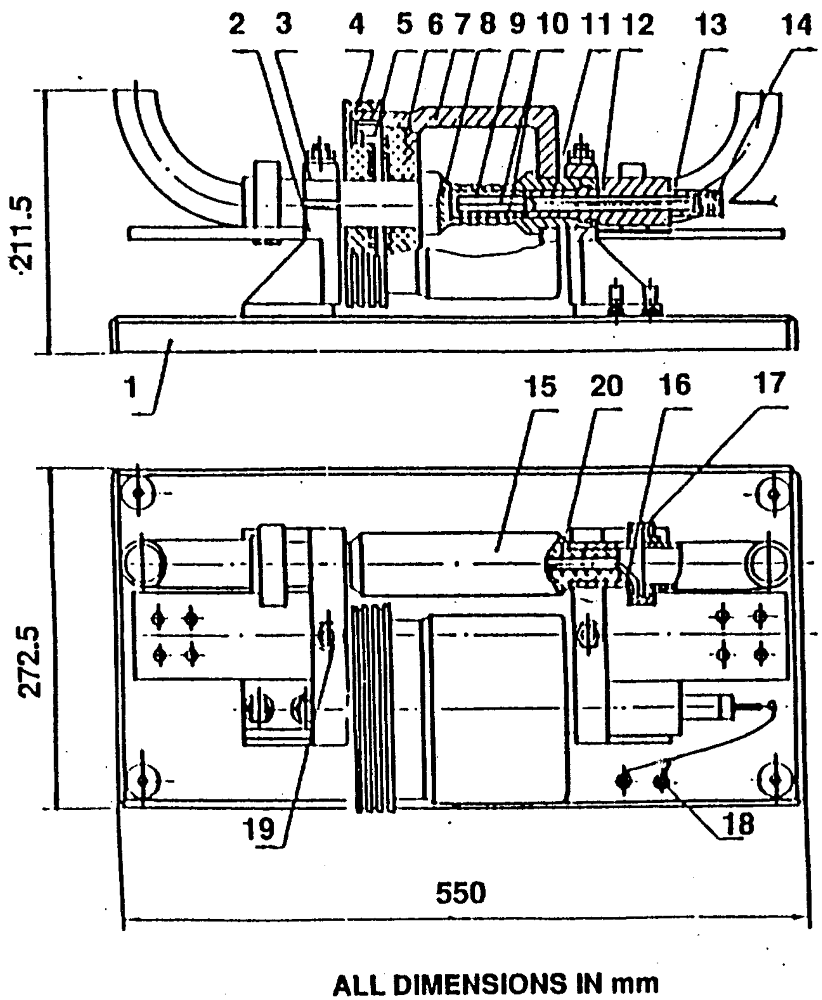
In response to a command for breaking the electrical circuit, which is fed from the MHD facility control system, the current pulses are fed to the electric blasting caps (10). During the electric blasting cap operation, a part of the bushing (8) is crushed, and the electric circuit is interrupted. An electrical arc occurs between the remaining bushing parts, which are clamped in the brackets (2), and the arc is intensively quenched by a shock wave and paraffin decomposition products.

The wire (16) in the jumper is exploded by current action, and the electrical circuit is interrupted. During current flow in the wire, the commutator space between the remaining bushing parts is deionized, and the insulation electrical strength becomes sufficient for withstanding the voltage occurring from the wire explosion, and the current commutation to a load (ballast resistance). The technical parameters for the breaker are listed in Table 5.

TABLE 5
BREAKER TECHNICAL PARAMETERS

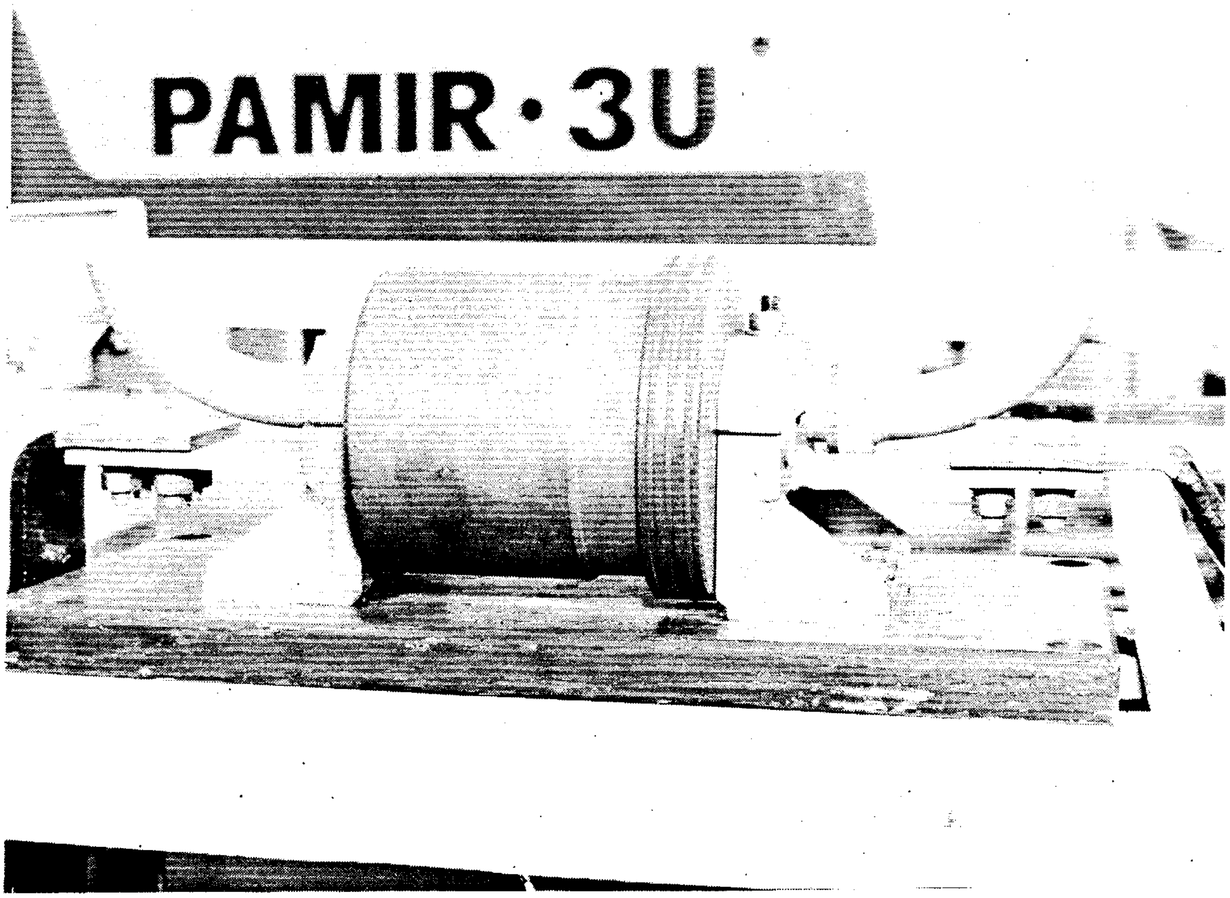
Parameter	Value
Rated voltage	2 kV
Maximal current during 1 s	20 kA
Mass	25.5 kg

BREAKER IM1-115VP-1.00.000



1-BASE;
2-BRACKET;
3-STRAP;
4-OUTER INSULATOR;
5- NUT;
6-INNER INSULATOR;
7-CASE;
8-BUSHING;
9-PARAFFIN CUP;
10-ELECTRIC BLASTING CAP ED-8;
11-FLEXIBLE PVC TUBE ϕ 5 mm;
12-CASING;
13-GAS VENT PIPE;
14-CASING CAP;
15-JUMPER;
16-WIRE PEV2 ϕ 0.8 mm;
17-COUPLING NUT;
18-TERMINAL KP-10;
19-NUT M12 (METRIC THREAD IN DIAMETER 12 mm;
20-FLEXIBLE PVC TUBE ϕ 3mm;

Figure 19 Breaker



P7580

Figure 20 Breaker Installed in the Facility

3.2.2 Contactor X-8F.01.05.000

The contactor is a pyrodynamic commutating device and is intended for closing the high-current, high-voltage circuits when control signals are fed to its actuating parts. The contactor is shown in Figure 21 mounted on the plate (8), which is made from a glass-cloth-base laminate. The fixed contact consists of two parts, with a clearance of 3 mm. A bronze comb (4), consisting of two parts, is attached in the head part of this contact. The contactor is shown in the photograph of Figure 22.

In the center of the plate (8), a steel bushing (6) is installed. A steel case (5) is screwed into the bushing. Two squibs (11), adapters (9), and plug (10), are screwed into threaded holes of the case. The closing movable element, made from a glass-cloth-base laminate rod and a copper contact (2), is inserted into a central hole of the case. An insulated liner (3) made from polyethylene film is installed into an air clearance between parts of the fixed contact (7) for the necessary electrical insulation strength. The liner is fixed to the plate (8) by four steel clamps (12).

In response to a command for closing the electrical circuit, which is fed from the MHD facility control system, current pulses are fed to the squibs (11), and the squibs operate. High pressure is generated in the central hole space of the case (5) between the plug (10) and the rod (1). Under action of this pressure, the rod and the movable contact (2) move to the fixed contact (7).

The movable contact breaks out the liner (3), and on the following movement, cuts into the teeth of comb (4) creating a current flow in the circuit through the fixed contact.

The movable contact cuts into the comb teeth until the rod (1) opens a cross-over hole in the case (5), and the pressure release occurs from the case central hole volume. The cross-over hole ends at adapter (9). If necessary for the removal of the squib explosion products in a safe direction, the vent pipes can be connected to the adapters (9).

The technical parameters for the contactor are listed in Table 6.

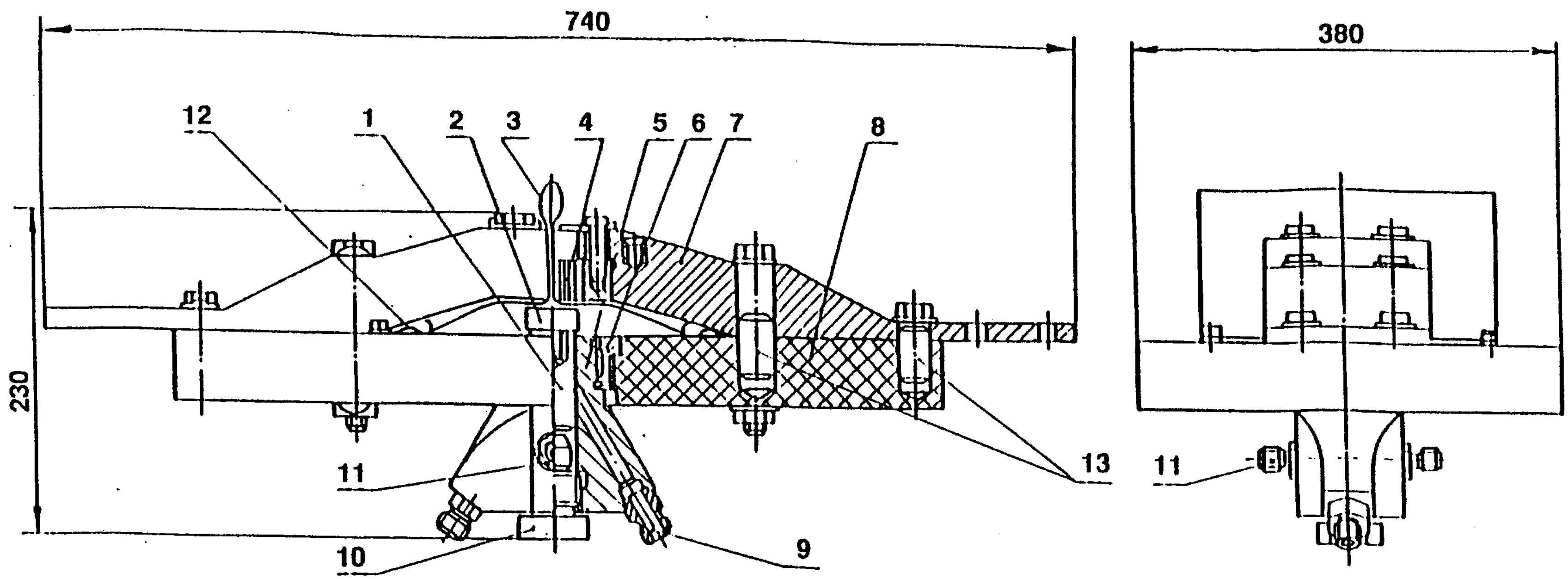
TABLE 6
CONTACTOR TECHNICAL PARAMETERS

Parameter	Value
Rated voltage	2 kV
Rated current during 10 s	40 kA
Mass	58 kg

3.2.3 Protection Unit IM-1-3.02.00.500

The protection unit is used for the dissipation of the energy that has accumulated in the magnet system at the end of the MHD facility operation and for a limitation of the overvoltage across its components. The protection unit consists of a system of diodes connected in parallel, and an RC-network with a ballast resistor connected in series. The protection unit principal view is given in Figure 23. The protection unit consists of a diode unit (6), a resistor (9), and a shunting unit (3) connected together by copper buses, according to the electrical schematic diagram of Figure 23.

CONTACTOR X 8F.01.05.000



ALL DIMENSIONS IN mm

1-ROD; 2-MOVEABLE CONTACT; 3-INSULATED; 4-COMB; 5-CASE; 6-BUSHING; 7-FIXED CONTACT; 8-PLATE; 9-ADAPTOR; 10-PLUG; 11-EXPLOSIVE CHARGE UDP2-3; 12-CLAMP; 13-PIN

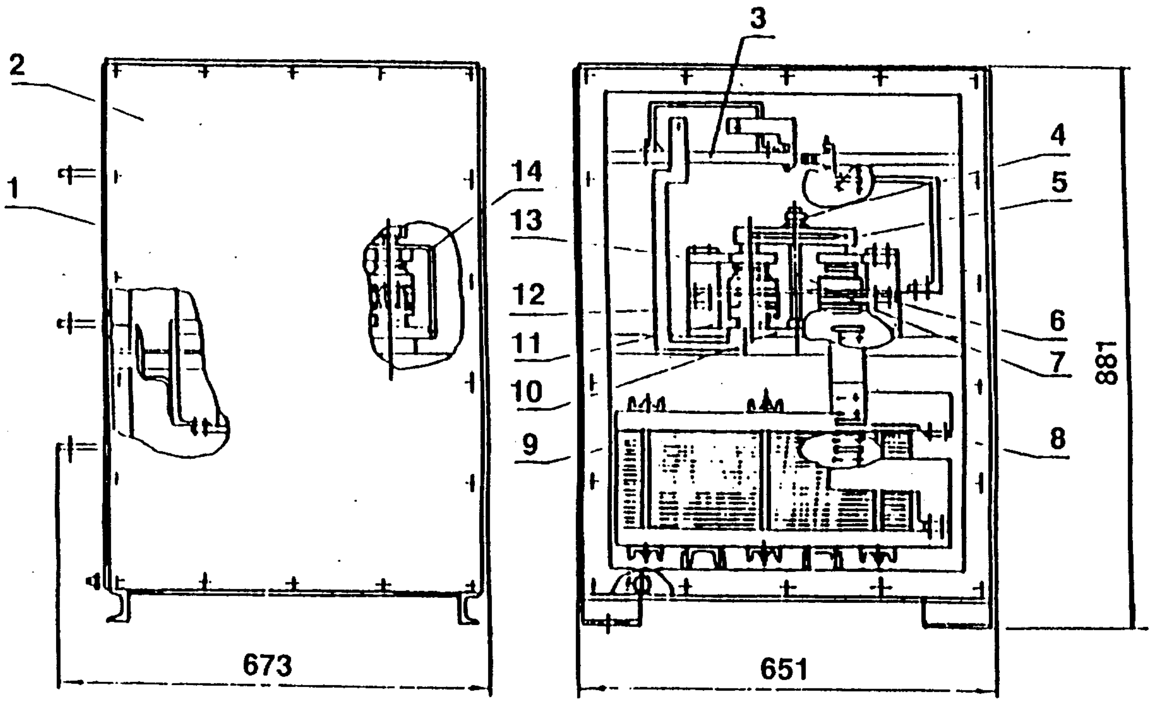
P7557

Figure 21 Contactor

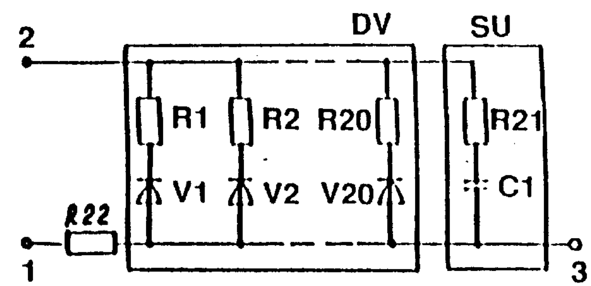
P7581

Figure 22 Contactor Installed in the Facility

PROTECTION UNIT IM1-3.02..00.500



SCHEMATIC CIRCUIT DIAGRAM



ALL DIMENSIONS IN mm

1-PANEL; 2-WALL; 3-SHUNTING UNIT (SU); 4-NUT 410; 5-ROCKER; 6-DIODE UNIT (DV); 7-STUD; 8-FRAMEWORK; 9-RESISTOR (R22); 10-BASE; 11-DIODE (V1...V20); 12-RESISTOR (RI...R20); 13-HEAT SINK; 14-BUS

P7556

Figure 23 Protection Unit

The diode unit consists of twenty diodes (11) connected in parallel. The resistors (12), which are made from a metal sheet, are connected in series with the diodes for current equalization in parallel paths. The metal sheet is stainless steel with a specific resistance of 0.75×10^{-6} Ω-m. In the design, the diodes, resistors, and heat-sinks (13) are collected in ten assembly units that are placed on the commonly conducting base (10). The assembly units are pressed in pairs by studs (7), rockers (5), and nuts (4). To avoid a failure of diodes, their bracing-force is checked by the arrowed line position on the rocker. After bracing, the end of the arrow shall be in line with a red mark on the rocker. The assembled units are connected together by flexible buses (14).

The resistor (9) is wound in a zigzag fashion by a stainless steel sheet, and braced by steel studs. The current leads are welded to the band ends. The resistor turns are insulated from each other by liners of a high-temperature mineral glass-reinforced plastic. The shunting unit (3) consists of a 100 μF capacitor and a 1.5 Ω Ni-Cr alloy resistor connected in series and placed on the electrically insulated base.

The protection unit case is made of a dust-tight and water-tight construction. All components are mounted on a framework (8) which is enclosed by walls (2) and a panel (1). The protection unit is connected in parallel to the magnet system. At the stages of initial excitation, self excitation, and the MHD facility operation to the load, a reverse voltage is applied across the protection unit. After the plasma generator operation ends, the inner resistances of the MHD channels rise sharply, and the diodes of the protection unit are connected in the conduction direction. The magnet system current begins to flow through the protection unit. For this case, a voltage is defined by the resistance of the R22 resistor (9) of Figure 23 and the limiting current, and does not exceed 2 kV. Simultaneously, the resistor limits the circuit currents in the case of diode electrical break-down.

The technical parameters for the protection unit are listed in Table 7.

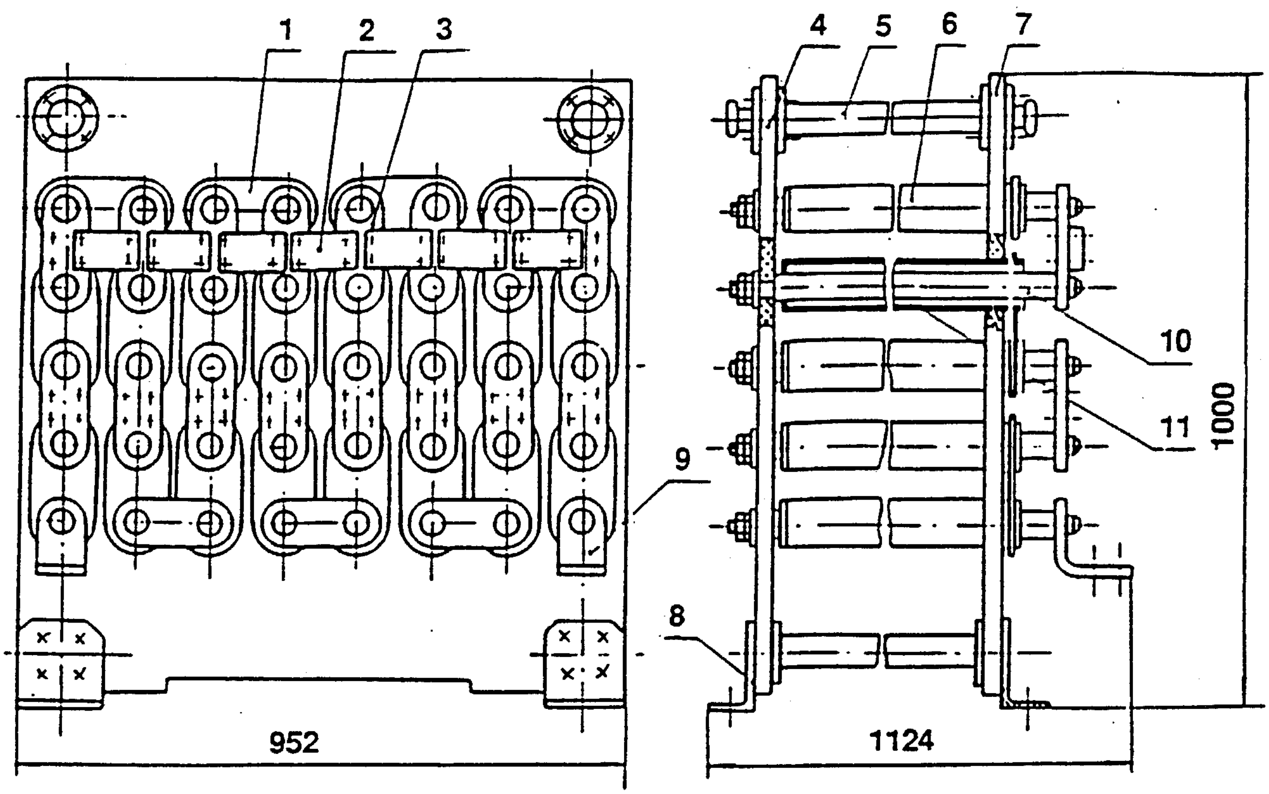
TABLE 7
PROTECTION UNIT TECHNICAL PARAMETERS

Parameter	Value
Maximal reverse voltage	2 kV
Maximal current drop per 0.33 s of exponential current fall	2 kA
Rated resistance between leads (1) and (3) of Figure 23	0.1±0.01 Ω
Power consumption	8 MJ
Unit mass	194 kg

3.2.4 Ballast Resistance IM1-051M.01.05.000

The ballast resistance is used to limit the magnet system current during the stage of the MHD facility operation with a load. The ballast resistor is made from stainless steel with a specific resistance of 0.75×10^{-6} Ω-m. The ballast resistance is shown in Figure 24. To decrease the resistor inductance, its parts are made as co-axial tubes (11) and rods (10) connected together by jumpers (1 and 3). The resistance parts are installed on glass-reinforced plastic walls (4 and 7) and fastened by ties. The resistance variation discreteness is made by installation of the demountable jumpers (2). The leads (9) serve for the connection of the resistance to the MHD facility circuit. The resistor attachment to the electrical equipment unit framework is made through the legs (8).

BALLAST RESISTANCE IM1-051M.01.05.000



ALL DIMENSIONS IN mm

1,3-JUMPER; 2-DETACHABLE JUMPER; 4,7-WALL; 5-TIE;
6-RESISTANCE PART; 8-LEG; 9-LEAD; 10-ROD; 11-TUBE.

P7555

Figure 24 Ballast Resistance

The technical parameters of the ballast resistance are listed in Table 8.

TABLE 8
BALLAST RESISTANCE TECHNICAL PARAMETERS

Parameter	Value
Ohmic resistance by removable jumpers	40 mΩ
Resistance variation discreteness	2 mΩ
Rated current	16 kA
Power consumption	75 MJ
Mass	942 kg

3.3 DUMMY LOAD

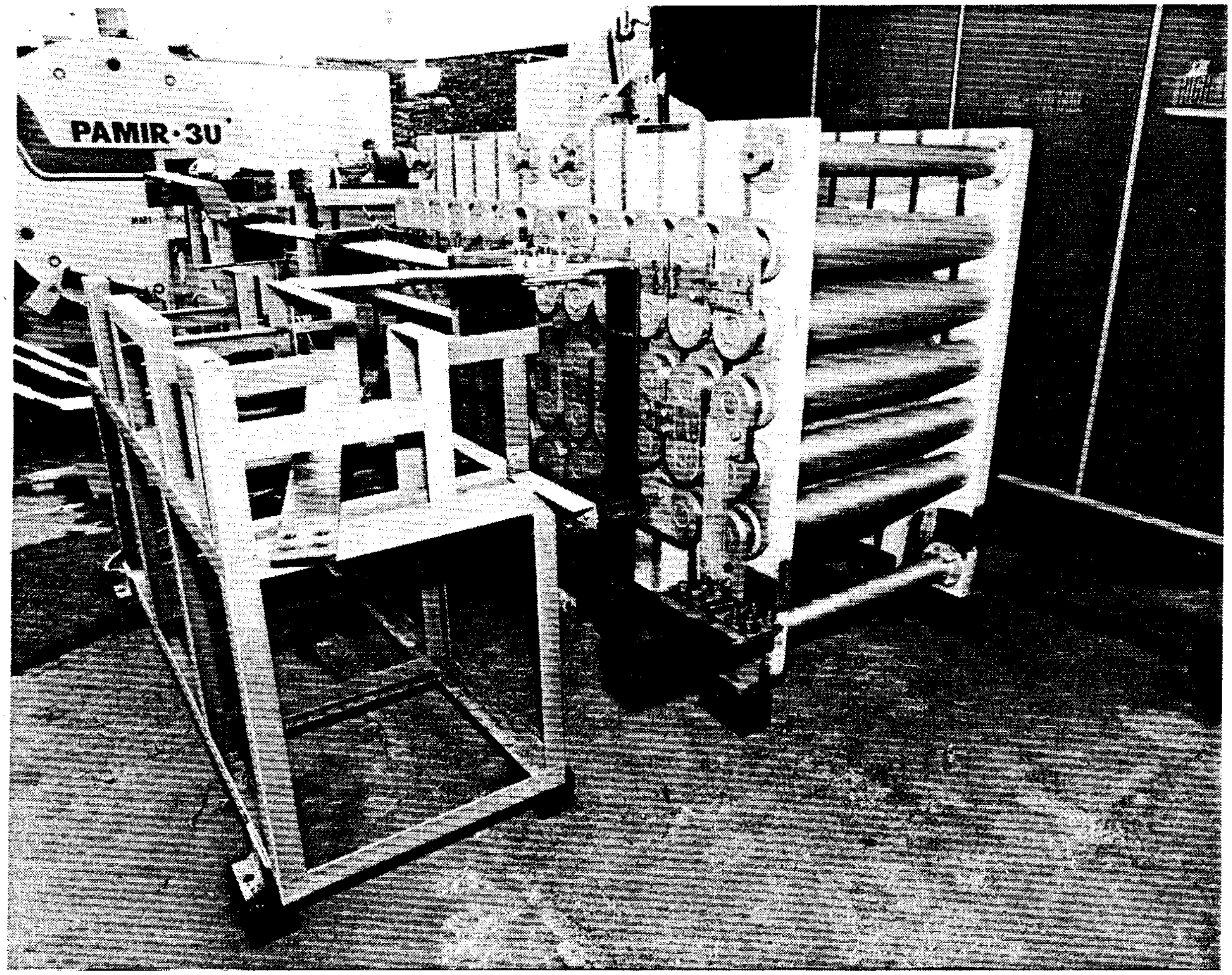
The dummy load was used during the acceptance tests of the Pamir-3U MHD Power System in Russia and in the United States. The dummy load is an active resistor made from stainless steel with a specific resistivity of 0.75×10^{-6} Ω-m. In order to reduce inductance, the dummy load resistor is made from co-axial tubes and rods connected together by jumpers. The resistor parts are installed on glass-reinforced plastic walls that are fixed together by braces. Discreteness of the resistance variation is achieved by the installation of demountable jumpers. The dummy load is shown in Figure 25. The technical parameters for the dummy load are listed in Table 9.

TABLE 9
DUMMY LOAD TECHNICAL PARAMETERS

Parameter	Value
Ohmic resistance by removed jumpers	15 mΩ
Resistance variation discreteness	1 mΩ
Maximal current	50 kA
Power consumption	100 MJ
Mass	1480 kg
Overall dimensions	1034 x 1138 x 1330 mm^3

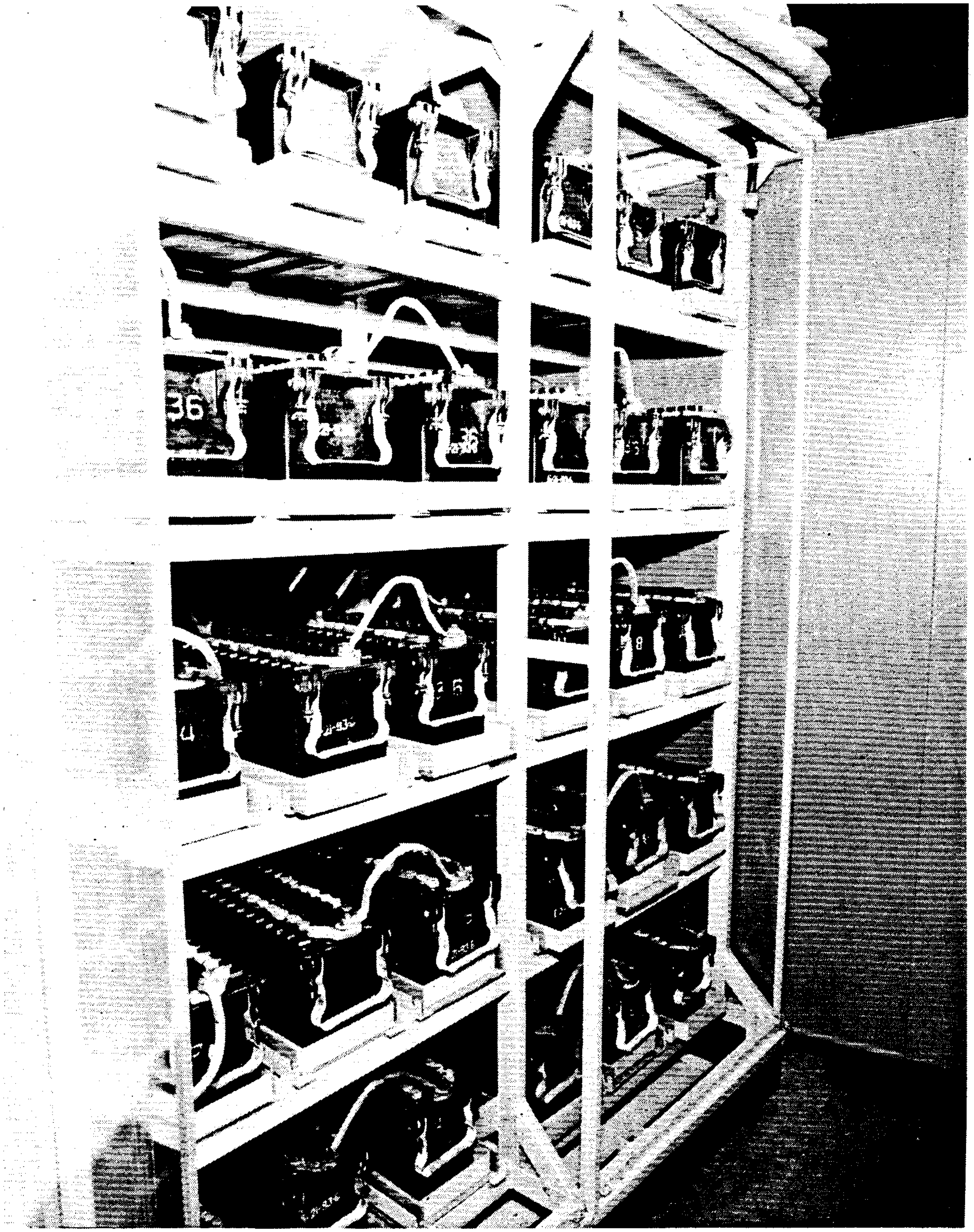
3.4 INITIAL EXCITATION SYSTEM

The Initial Excitation System (IES) is assembled as a modular unit in a metal cabinet with overall dimensions 2100 mm x 2100 mm x 1156 mm. Because the casing is made from metal doors along the whole cabinet perimeter, access zones are located around the cabinet on all four sides. The cabinet load-carrying structure is a stiff framework of removable shapes assembled as a cellular construction mounted on a load-carrying frame. In Figure 26, the IES cabinet with the batteries installed is shown. The IES consists of sixty batteries, which are Model No. CAM-28 aviation storage batteries.



P7586

Figure 25 Dummy Load



P7587

Figure 26 IES Cabinet with the Batteries Installed

Approximately two-thirds of the cabinet volume is occupied by the storage batteries, which are divided into five sections. Each section is occupied by one level of twelve storage cells that are connected in series by power buses and commutating power thyristors. A tray is installed in the lower part of the cabinet under the storage battery. The battery tray is protected by an acid-proof coating. The tray is designed to prevent any leaking battery acid from dripping on the floor. Each storage cell is installed in a separate tray that is protected by the acid-proof coating for the same purpose. In another part of the cabinet, the remaining IES components are located: a commutation device, a potential isolator, a five channel charging device, the electronic part of the potential isolator, a control board, cables, connection units, load resistors, a current commutator, transformers of the charging devices, and a fan.

The commutation device consists of two parts: an electronic part and an electro-mechanical part. The electronic part consists of five high power thyristors, installed on the common power positive voltage bus. The electro-mechanical part consists of a BA52-39 type automatic breaker, which is installed on the bracket for provision of convenient manual operation.

The power, signal, and supply cables are fed from the IES cabinet through holes in the load-carrying frame, and then connected with other parts of the MHD facility through cable trays or along the earth surface. The technical parameters for the IES are listed in Table 10.

TABLE 10
IES TECHNICAL PARAMETERS

Parameter	Value
Initial excitation energy	0.25 MJ
Resistive-inductive load	
Resistance (R)	59.0 mΩ
Inductance (L)	53.4 mH
Total rated voltage at the battery at the beginning of a discharge	288±10 V
Time for the current at the load to increase to 2.8 kA, not more than	1.6 s
Overall dimensions	2100 x 2100 x 1156 mm^3
Mass (without spares, tools and accessories)	up to 2600 kg

3.5 CONTROL, MEASURING, MONITORING, AND RECORDING SYSTEM

3.5.1 Introduction

The Control, Measuring, Monitoring, and Recording System (CMMRS) is designed for control of the Pamir-3U MHD facility and measurement of its parameters. The technical parameters for the CMMRS are listed in Table 11.

TABLE 11
CMMRS TECHNICAL PARAMETERS

Parameter	Value
Number of measuring and recording channels	14
Distribution of channels:	
- current	6
- voltage	4
- pressure	4
Number of channels with installation of additional Galvanic Isolation Device (GID)	16
Digitization frequency	100 Hz
Recording duration, not less than	12 s
Cut-off frequency of measuring channels at a level of - 3 dB, not less than	25 Hz
Number of control channels for feed of commands to the executive devices.	8
Distribution of Channels	
- IES turn on command (KPHB)	
- IES turn off command (KQ)	
- three commands for ignition of the plasma generators (KPG1, KPG2, KPG3)	
- command for connection of MHD channels (KZM1)	
- two commands for connecting the ballast resistor into the magnet circuit (KRU1, KRU2)	
Number of control channels of the MHD facility subsystem readiness, not less than	12
Number of control channels for commands to executive devices including plasma generators	12

The names of the measuring channels, range of input signals, and measurement error are given in Table 12.

TABLE 12
CMMRS CHANNEL MEASUREMENT ACCURACY

Channel Number	Parameter Measured	Parameter Symbol	Range	Measurement Error to A/D Converter Scale, not more than
1.	Magnet current	(TM)	0 to 25 kA	± 3.0 %
2.	MHD channel 1 current	(TK1)	0 to 30 kA	± 3.0 %
3.	MHD channel 2 current	(TK2)	0 to 30 kA	± 3.0 %
4.	Initial excitation current	(TNW)	0 to 3 kA	± 3.0 %
5.	Load current	(TN)	0 to 20 kA	± 3.0 %
6.	Load current	(TN)	0 to 20 kA	± 3.0 %
7.	K1, K2 MHD channel voltage	(NK)	0 to 1000 V	± 3.0 %
8.	Magnet voltage	(NM)	0 to 2000 V	± 3.0 %
9.	Load voltage	(NN)	0 to 1000 V	± 1.0 %
10.	PG1 pressure	(DGP1)	0 to 60 atm	± 3.0 %
11.	PG2 pressure	(DGP2)	0 to 60 atm	± 3.0 %
12.	PG3 pressure	(DGP3)	0 to 60 atm	± 3.0 %
13.	Voltage measurement reserve		0 to 1000 V	± 3.0 %
14.	Pressure measurement reserve		0 to 60 atm	± 3.0 %

The CMMRS is electrically isolated from the electrical equipment unit and the power unit. The CMMRS is also isolated from the initial excitation circuit. The isolation voltage is not less than 500 V.

3.5.2 CMMRS Composition and Design

The CMMRS consists of five main units: 1) measuring rack (MR); 2) final-control rack (FCR); 3) control rack (CR); 4) console panel (CP); and 5) monitoring personal computer (PC). The CMMRS composition incorporates cables, optical fibers, and a spare parts, tools and accessories (SPTA) set. The measuring rack, which is shown on the right in Figure 27, has the overall dimensions of 550 mm x 400 mm x 360 mm (height, width, length) and consists of seven two-channel galvanic isolation device (GID) plates; analog data collection unit DCU on the base of SD MS8201; and power supply unit PS1.1.

The final-control rack, which is shown on the left in Figure 27, has the overall dimensions of 550 mm x 450 mm x 360 mm and consists of: 1) Eight final-control modules - seven modules of ignition unit UECF1 to UECF7 and one module UIES of the IES control; 2) Transmitter-converter of digital data transmission device TCU1 (PDP) on the base of TC MS4101; 3) Transmitter-converter of digital data transmission RCU1 (PMPOUT) on the base of RC MS4101; 4) Matching unit IB2.1; 5) Power supply unit PS2; and 6) Power supply unit PS2.1.

The control rack shown on the left in Figure 28 has the overall dimensions of 250 mm x 450 mm x 360 mm and consists of: 1) Control interface plate IB3.1; 2) Measuring interface plate IB3.2; 3) Receiver-converter of analog data collection unit RCU2 (CDPMP) on the base of RC MS8201 ; 4) Transmitter-converter of a digital data transmission unit TCU2 (PDP) on the base of TC MS4101; 5) Transmitter-converter of a digital data transmission unit RCU2 (PMPIN) on the base of TC MS4101; and 6) Power supply unit PS3.1.

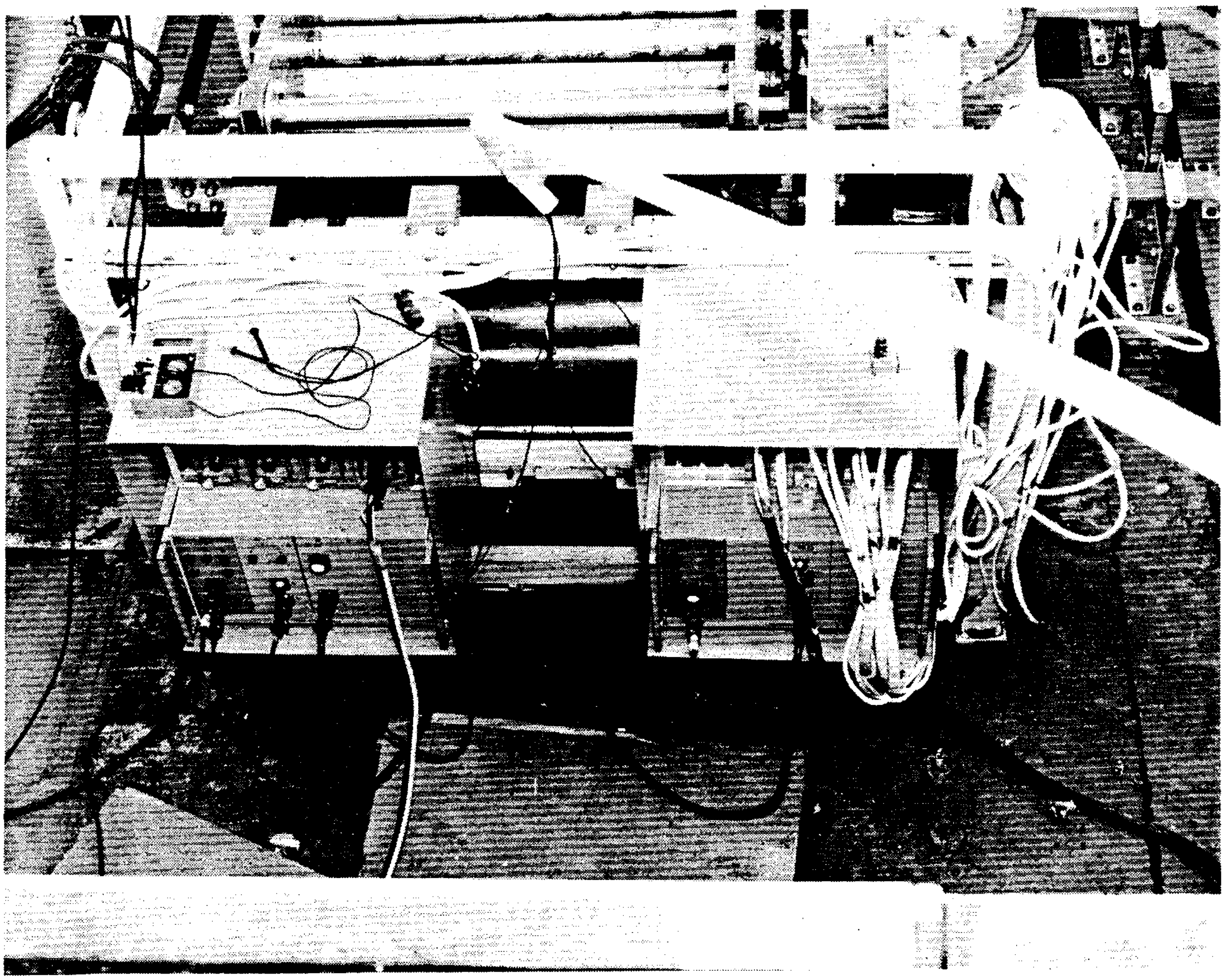


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Figure 27 CMMRS Measuring Rack and Final Control Rack

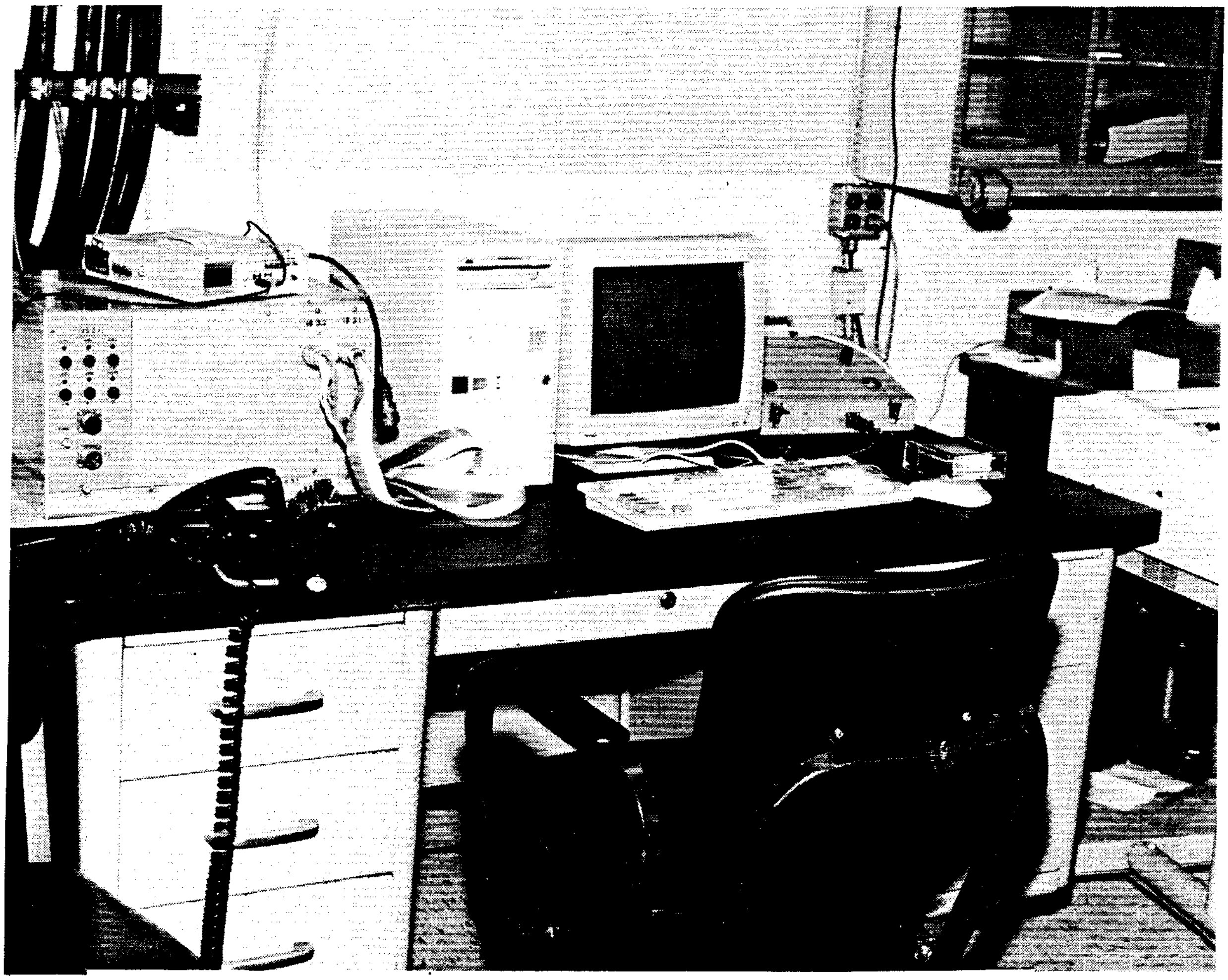

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Figure 28 CMMRS Control Rack and Console Panel

The console panel shown on the right in Figure 28 has the overall dimensions 150 mm x 300 mm x 250 mm. The equipment located on the console panel includes a light-emitting diode indicator "WORK"; neon indicator "POWER"; ignition lock "IGNITION LOCK"; and "START" button.

3.5.3 CMMRS Arrangement

The CMMRS block diagram is shown in Figure 29. The block diagram elements are listed in Figure 30. The CMMRS can be divided into two parts by convention: 1) control system that consists of the final-control rack, TCU2, RCU3, IB3.1 units of the control rack, as well as the console panel and 386 PC; and 2) measuring system that consists of the measuring rack, RCU2, IB3.2 units of the control rack, as well as IBM 386 PC. The CMMRS location at the MHD facility is: the final-control rack and the measuring rack are placed on the EEU; and the control rack, CP and PC are located in the control room. The minimum requirements for the CMMRS computer are a 386 type processor chip, 640 kB of RAM, 3 MB of ERAM, a hard disk with storage capacity of 116 MB, and a floppy disk drive that can accommodate 1.44 MB, 3.5" floppy disk.

The communication between the racks located on the EEU and the control rack located in the control room is provided by three optical fibers, and two copper four-conductor cables. The power is supplied to the final-control rack and the measuring rack through one copper cable, and the power is supplied to the final-control amplifiers UECF1 to UECF7 and UIES8 through the other copper cable. Measured information is transmitted from transducers to the PC through the first optical fiber cable The control signals are sent to the executive device through the second optical fiber cable. The information from executive devices is sent to the PC through the third optical fiber cable.

The Pamir-3U MHD facility control is performed using a 386 PC through the interface plate IB4, which is placed inside the PC. Figure 31 shows a top level CMMRS logic diagram. The control of the Pamir-3U MHD facility operation is performed according to the logical circuit shown in Figure 32. The same control program CMMRS.EXE is used for both the firing runs and the "cold" runs. The program is written in the programming language Turbo-Pascal 7.0. The CMMRS is a program controlled device, and from a logical point of view, it consists of input and output amplifiers, an optical fiber interface, an interface plate in the PC, and the PC. The input amplifiers (IUC, IUP, and IUV) provide the amplification and conversion of the signals from current, pressure, and voltage transducers (B1 to B17), as well as electrical isolation between input and output. The output amplifiers (UECF, UIES) generate signals for ignition of the pyrotechnical equipment (PG1, PG2, PG3, ZMI, ZM2, RU1, and RU2), and the IES start and stop.

An optical fiber interface consisting of RCU1, TCU1, RCU3, TCU2, IB2.1, IB3.1, and IB3.2 provides transmission of signals from IB4 to the output amplifiers and back, analog/digital conversion (DCU) of signals from the input amplifiers, and transmission of a digital signal (RCU2, IB3.2) to IB4. The optical fiber interface provides protection of communication lines of the measuring and the final-control racks against voltage spikes during the MHD facility operation.

The interface plate IB4 in the PC is two parallel 24-bit ports with byte data transmission from the PC and back. A timer is placed on the interface plate, which forms the interruption signals, IRQ3, of 100 Hz frequency needed for the operation of the program for the firing run control. The first parallel port receives the signals through IB3.2 from A/DC (RCU2). The second parallel port generates the signals through IB3.2 to the executive devices, and receives readiness signals from all units of the CMMRS.

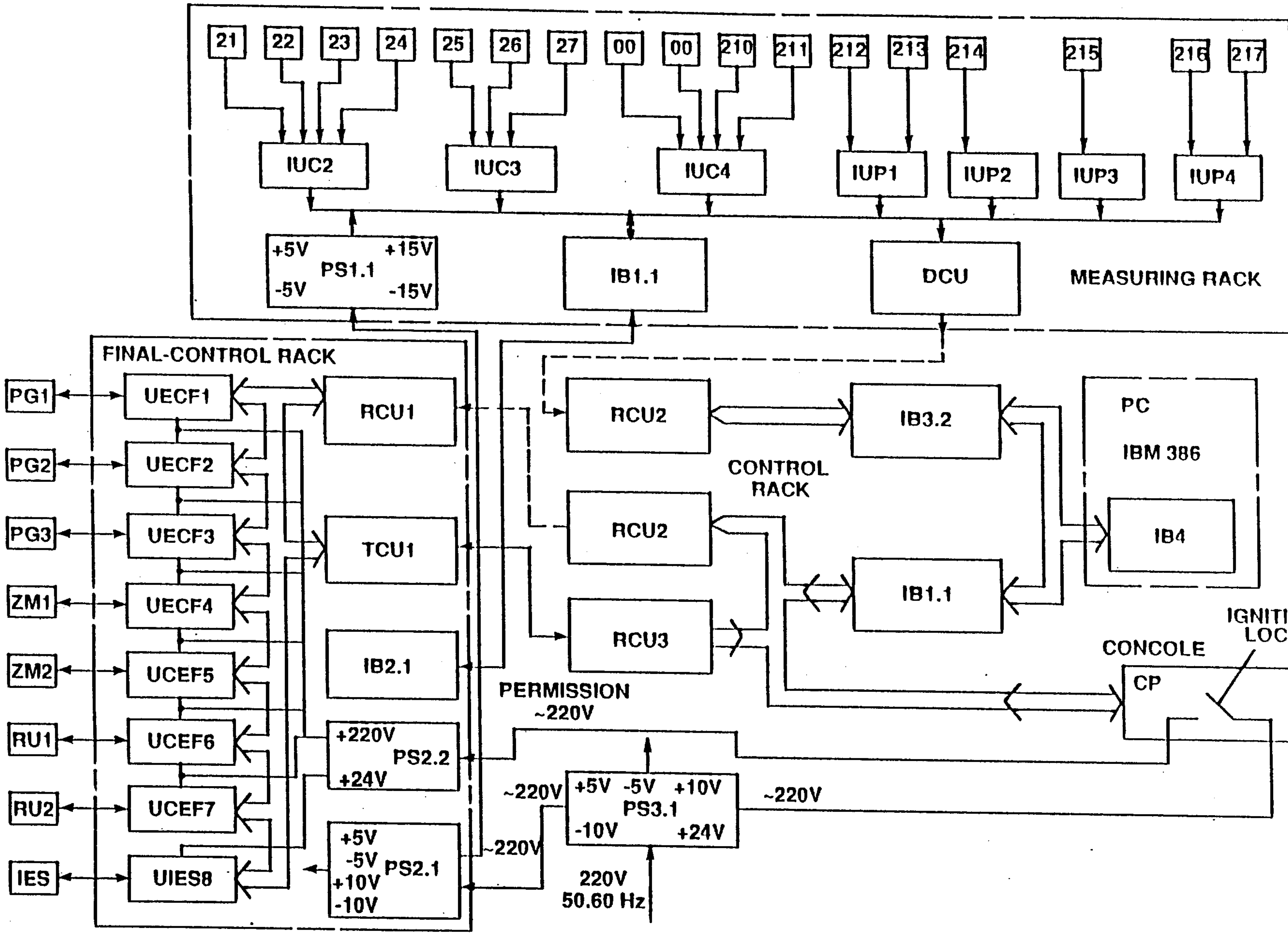

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Figure 29 CMMRS Block Diagram

LIST OF ELEMENTS

CMMRS PAMIR-3U RAN 36.00.000.E1

Revtov A.N. BUILDING CIRCUIT DIAGRAM

Disig-nation	Name	Num	Comment
B1	SHUNT 75SHSM 7500A	1	In1.1
B10	SHUNT 75SHSM 7500A	1	Ik2.1
B11	SHUNT 75SHSM 7500A	1	Ik2.2
B12	PRESSURE TRANSDUCER MD-60T	1	
B13	PRESSURE TRANSDUCER MD-60T	1	
B14	PRESSURE TRANSDUCER MD-60T	1	
B15	VOLTAGE DIVIDER	1	Um
B16	VOLTAGE DIVIDER	1	Um
B17	VOLTAGE DIVIDER	1	Um
B2	SHUNT 75SHSM 7500A	1	In1.2
B3	SHUNT 75SHSM 7500A	1	In2.1
B4	SHUNT 75SHSM 7500A	1	In2.2
B5	SHUNT 75SHSM 3000A	1	Iies
B6	SHUNT 75SHSM 7500A	1	Ik1.1
B7	SHUNT 75SHSM 7500A	1	Ik1.2
B8	SHUNT 75SHSM 6000 A	1	Im1
B9	SHUNT 75SHSM 6000 A	1	Im2
CP	CONCOLE PANEL	1	
DCU	DATA CONVERTER UNIT	1	
IB1.1	INTERFACE BOARD 1.1	1	
IB2.1	INTERFACE BOARD 2.1	1	
IB3.1	INTERFACE BOARD 3.1	1	
IB3.2	INTERFACE BOARD 3.2	1	
IB4	INTERFACE BOARD 4	1	
IUC2	ISOLATION UNIT FOR CURRENT	1	
IUC3	ISOLATION UNIT FOR CURRENT	1	
IUC4	ISOLATION UNIT FOR CURRENT	1	
IUP1	ISOLATION UNIT FOR PRESSURE	1	
IUP2	ISOLATION UNIT FOR PRESSURE	1	
IUV3	ISOLATION UNIT FOR VOLTAGE	1	
IUV4	ISOLATION UNIT FOR VOLTAGE	1	
PC	PERSONAL COMPUTER	1	
PS1.1	POWER SUPPLY 1.1	1	
PS2.1	POWER SUPPLY 2.1	1	
PS2.2	POWER SUPPLY 2.2	1	
PS3.1	POWER SUPPLY 3.1	1	
RCU1	RECEIVER CONVERTER UNIT	1	PMFOUT
RCU2	RECEIVER CONVERTER UNIT	1	CDFMF
RCU3	RECEIVER CONVERTER UNIT	1	PMPIN
TCU1	TRANSMITTER CONVERTER UNIT	1	
TCU2	TRANSMITTER CONVERTER UNIT	1	
UECF1	UNIT OF EXPLOSIVE CHARGES FIRING	1	
UECF2	UNIT OF EXPLOSIVE CHARGES FIRING	1	
UECF3	UNIT OF EXPLOSIVE CHARGES FIRING	1	
UECF4	UNIT OF EXPLOSIVE CHARGES FIRING	1	
UECF5	UNIT OF EXPLOSIVE CHARGES FIRING	1	
UECF6	UNIT OF EXPLOSIVE CHARGES FIRING	1	
UECF7	UNIT OF EXPLOSIVE CHARGES FIRING	1	
UIES8	UNIT OF INITIAL EXITATION SYSTEM	1	

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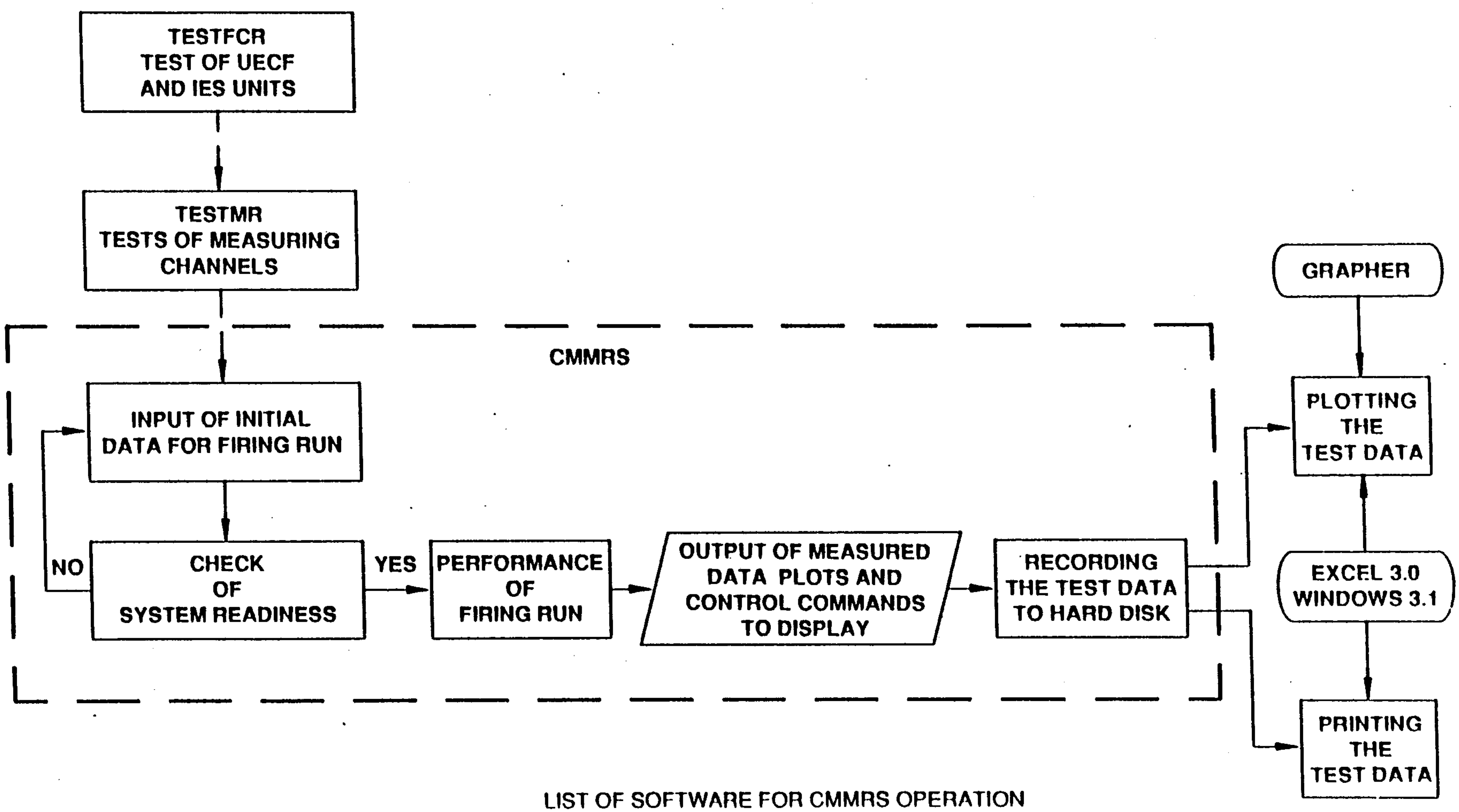
Figure 30 List of Block Diagram Elements



LIST OF SOFTWARE FOR CMMRS OPERATION

1. CMMRS. EXE - COMPUTER CODE FOR MHD POWER SYSTEM OPERATION CONTROL AND DATA ACQUISITION
2. TESTFCR. EXE - COMPUTER CODE FOR VISUAL TESTING THE UNIT OF EXPLOSIVE CHARGES FIRING AND IES
3. TESTMR. EXE - COMPUTER CODE FOR VISUAL TESTING THE MEASURING CHANNELS OPERATING ABILITY
4. GRAPHER - SOFTWARE FOR PLOTTING THE FIRING RUN DATA
5. EXEL 3.0 - SOFTWARE FOR PRINTING AND PLOTTING THE FIRING RUN DATA
6. WINDOWS 3.1 - SOFTWARE FOR EXEL OPERATION

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Figure 31 CMMRS Top Level Logic Diagram

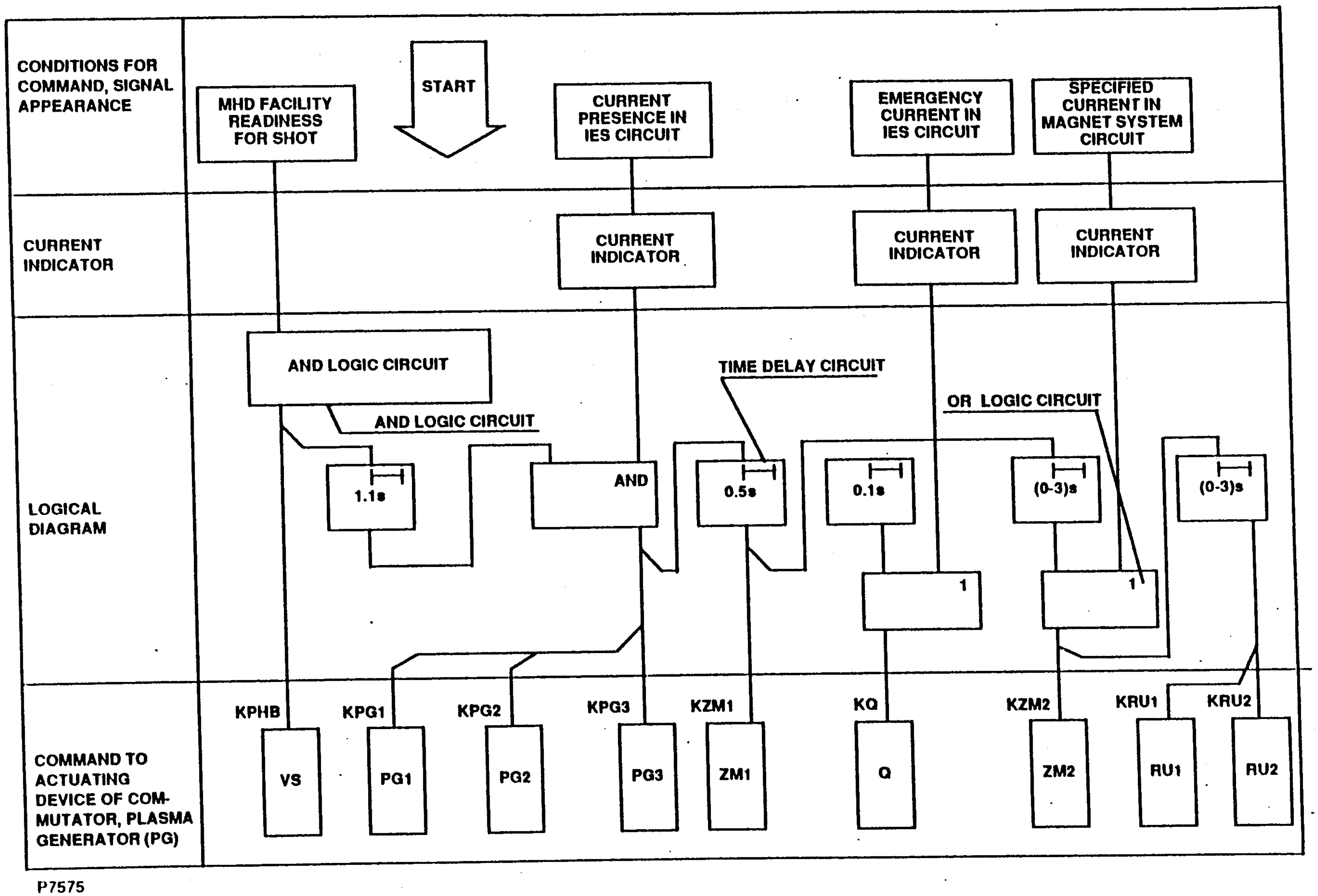

Figure 32 CMMRS Logic Diagram

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4.0 HARDWARE FABRICATION

The hardware for the Pamir-3U facility was manufactured, developed, and/or assembled by the Russian organizations described in Section 2.2. The plasma generators were manufactured by Soyuz. The fabrication of the plasma generators, including the DE-91 igniters, the OE-72 charges, and the GP77.01-5B plasma generator cases, is described in Section 4.1.

The MHD channels and the magnet system were fabricated by Nizhny Novgorod. The fabrication of the MHD channels is described in Section 4.2. The magnet system fabrication description is included in Section 4.3.

The electrical equipment unit was also manufactured at Nizhny Novgorod, and is described in Section 4.4. The Initial Excitation System (IES) and the Control, Measuring, Monitoring, and Recording System (CMMRS) were developed and/or manufactured at IVTAN. Their fabrication is described in Sections 4.5 and 4.6, respectively.

4.1 PLASMA GENERATOR

The plasma generators, developed and manufactured at Soyuz, are described in Section 3.1.1. The manufactured items include the plasma generator igniters, charges, and cases, described in Sections 4.1.1, 4.1.2, and 4.1.3, respectively. The random firing tests to which the plasma generators were subjected are described in Section 4.1.4.

In the process of manufacturing the plasma generators for the Pamir-3U facility, an accident took place at the plant producing the propellant charges, Soyuz. The accident resulted in a modified Preliminary Acceptance Test Program in Russian. Because IVTAN was able to use some charges from inventory for the Preliminary Acceptance Tests in Russia, a decision was made to perform the Preliminary Acceptance Tests without waiting for the Soyuz plant to be rebuilt.

However, in order to complete the Preliminary Acceptance Tests, all of the available OE-72 type charges and some of the OE-304 type charges, which have shorter burning durations, were required. Nevertheless, the construction parameters for the OE-304 charges permitted their use in the Pamir-3U facility.

4.1.1 DE-91 Igniter

Fabrication of igniters for the GP-77 plasma generators was performed according to the Igniter Technical Conditions DE91.TU.[1] The fabrication process consists of three stages: manufacture of igniter cases from aluminum sheet, filling the cases with 350 g of black powder for each case, and sealing the cases containing the sample of black powder.

The batch of igniters DE 91/11-90-L used for acceptance tests of the Pamir-3U MHD facility was fabricated in April, 1990 at Soyuz. The following checks and tests were performed during the manufacturing process of the igniter batch: certification of raw materials; check-out of igniters for leakage; and firing tests for operation without failure.

A leakage check and firing tests for operation without failure of DE-91 igniters were performed for the purpose of verification of the required quality of the manufactured batch of the igniters.

4.1.1.1 Leakage Check of the Igniters

The following procedures were performed:

1) ten igniters were taken from the batch;

2) the mass of each of the igniters was determined; the allowable igniter mass is 350 ± 5 g;

3) the igniters were put into a tank filled with water having a temperature +20°C, and were kept under water for four hours;

4) the igniters were then taken out of the water, and all water was thoroughly removed from the igniter surfaces;

5) the mass of each of the igniters was determined; no mass gain was allowed; and

6) the igniters were then opened, and a visual inspection of the powder was performed; there was no wet powder in the igniters.

According to the results described in steps five and six, the batch of igniters DE 91/11-90-L met the leakage requirements.

4.1.1.2 Firing Tests of the Igniters for Operation Without Failure

The following procedures were performed:

1) ten igniters were taken from the manufactured batch and put into a thermostat at a temperature of 20°C;

2) the igniters were kept in the thermostat for 6 hours;

3) after thermostating, the igniters were each installed in turn into a GP 77.01-120 front head fixed on a test jig;

4) the GP 77.01-60 cover was then installed on the front head, one of the threaded holes was closed with a plug and the UDP2-3 squib was installed into another threaded hole and connected to the ignition circuit; and

5) the igniters were fired by the application of a current pulse to the squib.

All of the igniters that were tested operated without any failure. According to the results obtained, the 11-90-L lot of the DE 91 igniters was approved for acceptance tests of the Pamir-3U MHD facility.

4.1.2 OE-72 Charge

Fabrication of the OE-72 charges for the GP-77 plasma generators was performed according to the Charge Technical Conditions, OE72.TU[1]. The fabrication process consists of three stages: manufacture of plasma-generating propellant BP-10, extrusion of the grain blanks, machining the propellant grains, and coating the blanks with cotton yarn impregnated with an epoxy resin.

The following checks and tests were performed during the fabrication process of the charge batch:

1) certification of raw materials;

2) determination of the actual burning rate for the propellant specimens in a manometric vessel having constant pressure;

3) determination of the actual propellant chemical composition;

4) determination of the actual propellant mass density;

5) propellant charge continuity test to detect cavities and cracks by ultrasonic or radiographic techniques;

6) quality test of the propellant and protective coating binding by an ultrasonic technique; and

7) measurement of the sizes and weights of the finished grains to meet drawing specifications.

Two batches of the OE-72 charges were manufactured for the acceptance tests of the Pamir-3U MHD facility during the July to October 1994 time frame. The batches were designated as 5-94-L (18 charges) and 6-94-L (17 charges). Two charges were taken from the 5-94-L batch and three charges were taken from the 6-94-L batch for random firing tests.

4.1.2.2 Analysis of the BP-10F Propellant Parameters for the 5-94-L and 6-94-L Batches

The main parameters of the BP-10F plasma generating propellant are the burning rate and the power complex, which is the product of electrical conductivity of the combustion products and the plasma flow velocity squared at the MHD channel inlet. For a solid propellant, the burning surface recedes in a direction perpendicular to the burning surface. The rate at which this surface recedes is called the "burning rate."[2]

4.1.2.2.1 Determination Method of the Parameters

The propellant burning rate is measured when propellant samples are combusted in a vessel that is pressurized by nitrogen at a constant pressure in the range of the plasma generator combustor pressure. The propellant samples are taken from the propellant charge blanks during their machining.

The propellant burning rate depends on the combustion pressure and the propellant temperature. The pressure dependence of the burning rate has the following form:

$$U = A \times P^B \qquad [1]$$

where P is the combustion pressure and A and B are empirical coefficients. The temperature dependence of the burning rate has the following form:

$$A = A1 \times T_0/(T_0 - T_p + 20) \qquad [2]$$

where A1 is the factor A at a temperature of 20°C, T_p is the propellant temperature in °C, and T_0 is an empirical coefficient.

The empirical coefficients A, B and T_0 depend on numerous factors such as raw material parameters and parameters for the propellant manufacturing process. Therefore, the burning rate of a particular lot of charges is not a well predicted value, but has variations relative to some average value. The variations are random quantities and, for double base propellant, are usually within a range of ± 5 %.

At the stage of machining the propellant grain, the propellant samples are taken from the propellant blanks and analyzed for definition of the actual chemical composition. The chemical composition data are used in the calculation of thermodynamic and electrophysical parameters of the combustion products in the plasma generator combustor, nozzle, and MHD channel.

The power complex of the plasma generating propellant combustion products depends on the combustor pressure and on the actual chemical composition of the propellant. The quantity of each propellant component shall be within the limits specified below in Table 13 Variations in the propellant are random, and depend on the equipment used for the propellant manufacturing. Variations in the propellant's chemical composition primarily control the conductivity of the propellant combustion products. The plasma flow velocity moderately depends on variations in the composition. The calculated estimate of the impact of the variations of the main components of the BP-10F propellant on the power complex is shown in Figure 33. The largest influence is exerted by the content of the metal fuel, and by the content of nitrocellulose, as well as the content of different technological agents and stabilizers used to improve the chemical stability. Variations in the content of propellant components are not controlled, and contraction of the limits of component contents requires the development of new technological equipment or the development of a new technological process for the propellant manufacture.

TABLE 13
PLASMA GENERATING PROPELLANT BP-10 CHEMICAL COMPOSITION

Component	Mass Percent
Kolloxyline (Nitrocellulose)	30 to 36
Nitroglycerine	28 to 32
Diphenilamine	0.4 to 1.2
Aluminum-magnesium alloy (Al/Mg - 95/5)	21 to 24
Magnesium oxide (MgO)	0.3 to 0.8
Cesium nitrate ($CsNO_3$)	9 to 13

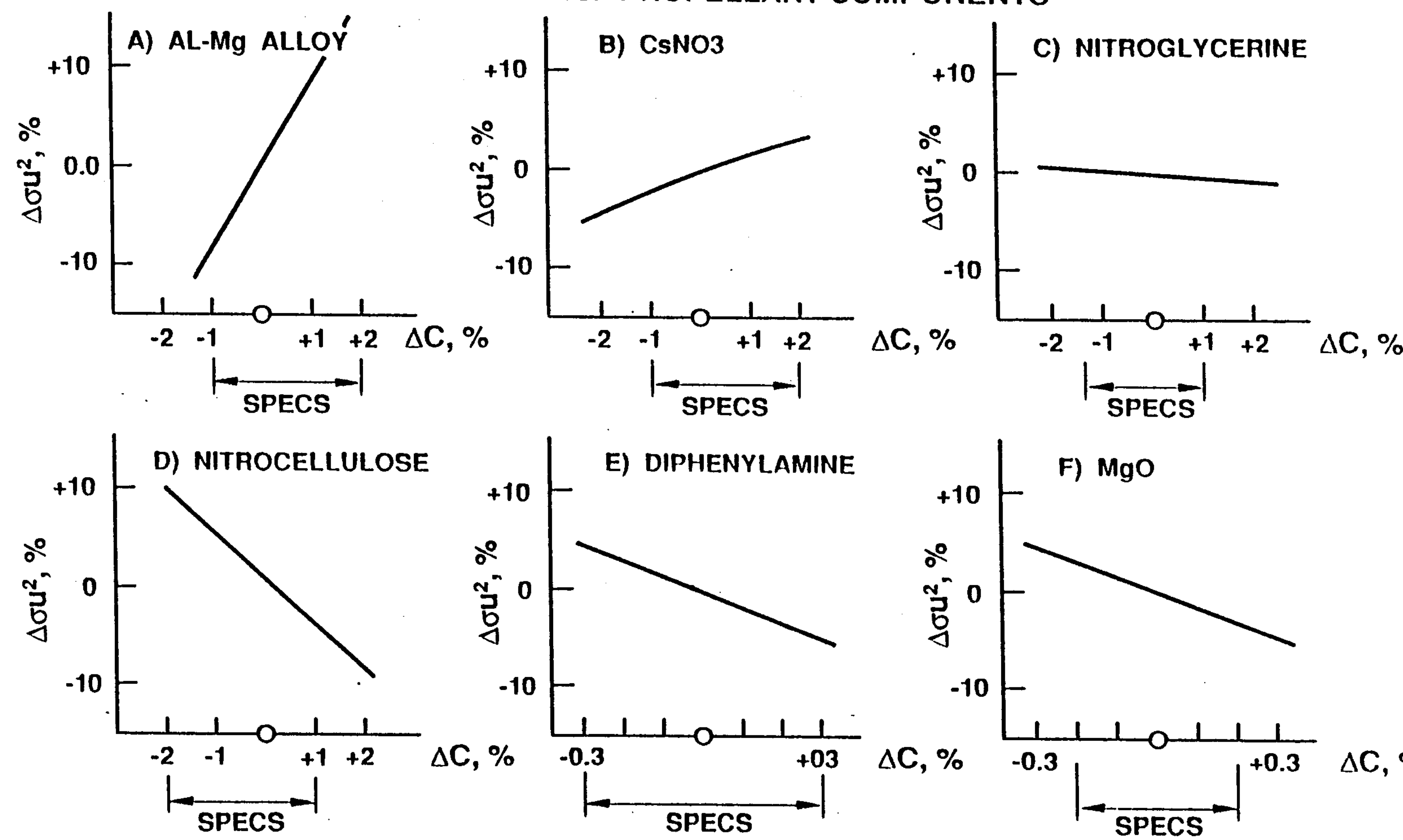
4.1.2.2.2 Results

The results of the experimental definition of the propellant burning rate at a combustion pressure of 41 atm and a propellant sample temperature of 20°C, and the results of the power complex calculation on the basis of the actual propellant chemical composition at a combustor pressure of 4 atm and with a nozzle expansion ratio of 3.4 are given in Table 14. The power complex parameter used in Figure 33 and Table 14 is a method for evaluating the performance of the plasma generator charge. The parameter, σu^2, is the electrical conductivity of the gas multiplied by the velocity squared. The power complex is usually calculated at the entrance to the MHD channel. If all other relevant parameters are equal, the higher power complex at the MHD channel entrance, in general, the higher the power produced by the MHD channel.

TABLE 14
RESULTS OF BURNING RATE TESTS AND POWER COMPLEX CALCULATIONS

Batch Number of BP-10F Propellant OE-72 Charges	Burning Rate at P_c = 41 atm (mm/s)	Power Complex (mho/m) $(km/s)^2$
5-86-L	12.035	295.0
24-86-L	11.96	312.0
32-86-L	11.82	313.2
41-86-L	12.225	308.8
304-86-L	11.74	329.6
5-87-L	12.085	341.2
22-87-L	12.21	339.6
25-88-L	12.64	368.0
26-88-L	12.605	356.0
31-88-L	12.51	356.2
42-88-L	13.165	347.9
8-89-L	12.23	351.8
37-89-L	12.42	347.0
48-89-L	12.63	328.3
7-90-L	12.2	330.8
5-94-L	11.64	318.6
6-94-L	11.765	305.4
Average value	12.23	332.32
Minimal value	11.64 (-4.82%)	295.0 (-11.23%)
Maximal value	13.165 (+7.65%)	368.0 (+10.74%)

POWER COMPLEX σu^2 DEPENDENCE ON CONTENT VARIATION OF THE MAIN BP-10F PROPELLANT COMPONENTS



$\Delta\sigma u^2$ - VARIATION OF POWER COMPLEX, %

ΔC - VARIATION OF PROPELLANT COMPONENT, %

SPECS - RANGE OF COMPONENT VARIATIONS LIMITED BY SPECIFICATIONS FOR BP-10F PROPELLANT

O - RATED CONTENT OF COMPONENT

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Figure 33 Calculation of the Estimated Impact of Variations of the Main Components of BP-10F Propellant on the Power Complex

4.1.2.2.3 Analysis of Defined Parameters

Burning rate:

The manufactured batches of the OE-72 charges are low-burning; that is, their burning rate is lower than the average value. The 5-94-L batch has the lowest burning rate of all of the batches of BP-10F propellant manufactured since 1986 for geophysical investigations. Because the combustor pressure depends, approximately, on the burning rate squared, the lower burning rate will cause the combustor pressure to be 8 to 10% lower than the combustor pressure in the batches having a nominal (average) burning rate such as the 48-89-L batch for example. Considering that the burning rate may be controlled by the propellant temperature (burning rate change is ~ 0.33 %/ °C), combustor pressure obtained from the batch having an average burning rate at a charge temperature of 20°C, may be achieved by temperature conditioning the propellant charges of the 5-94-L and 6-94-L batches at a temperature of 35°C.

Power complex:

The manufactured batches of the OE-72 charges have a calculated power complex that is lower than the average value, such as the 48-89-L batch with a power complex of 328.3. The lower power complex may cause a decrease in the output parameters of the MHD facility in comparison with the propellant batches having average burning rates.

During the development of the BP-10F plasma generating propellant, the chemical composition was chosen to optimize the collection of electrophysical, physical-chemical, mechanical, ballistic, technological and operational parameters. The modification of the BP-10F chemical formula for the objective of a guaranteed average level of the power complex, or a reduction of the limits on the range of the propellant components is similar to the development of a new plasma generating propellant. This more extensive technical development could not be performed within the framework of this program.

4.1.3 Case GP77.01-SB

The case for the GP-77 plasma generator was fabricated according to "The Plasma Generator Case, GP77, Technical Requirements GP77.TU".[1]

The following checks and tests were performed during the fabrication process of a batch of the plasma generator cases:

1) certification of raw materials and determination of strength parameters for specimens;

2) complete control of all welds by X-ray;

3) leakage test of each case by applying a pressure of 0.2 to 0.5 atm;

4) strength test of each case by applying an operating pressure of 4 to 6 MPa;

5) design clearance checks; and

6) tightening torque control for threaded joints according to the Design Drawings for GP-77.

The batch of the plasma generator cases was fabricated during January to July, 1994. The cases numbered 9401 - 9412 were intended for acceptance tests in the United States. The cases

numbered 9413 - 9416 were used for the random firing tests performed at the Soyuz in October 1994.

4.1.4 Random Firing Tests

In addition to the Preliminary Acceptance Test Program in Russia at the Geodesiya test site and the Acceptance Test Program in the United States at the Aerojet test site, both of which included the entire Pamir-3U MHD facility, a set of random tests were performed on individual plasma generators as well as on a one-channel MHD system with a plasma generator. These random tests are described below. The random tests were performed from 6 to 28 October 1994 at the Soyuz test site. The purpose of the tests was to check out the GP-77 plasma generator operation with OE-72 charges from the newly made 5-94-L and 6-94-L batches at different thermostating temperatures, and to estimate the ballistic and energetic performances.

Five OE-72 charges from the newly made batches were tested to confirm the operational ability of the thirty charges supplied to Textron Defense Systems. The test results are presented in Tables 15 and 16. At the same time, an OE-72 charge from the existing 48-89-L batch was tested for comparison of the energetic performance. Charges from the 48-89-L batch were used during the Pamir-3U MHD facility test on 10 August 1994 for the Preliminary Acceptance Tests in Russia, and produced good results.

The firing tests were performed in two steps: firing runs at an open test site (ballistic tests); and firing runs of a GP-77 plasma generator as a part of one-channel MHD facility "IM-1" (MHD tests).

TABLE 15
BALLISTIC TEST RESULTS

Test No.	Charge Batch	Thermostating Temperature (°C)	Nozzle Throat (cm^2)	Plasma Generator Average Pressure (atm)	Plasma Generator* Operating Time (s)
1	5-94-L	+5	73.48	40.46	9.54
2	6-94-L	+35	73.48	46.32	8.24

* Operating time was based on measured results obtained from the computer data system used to record the test results

TABLE 16
MHD TEST RESULTS

Test No.	Charge Batch	Thermostating Temperature (°C)	Plasma Generator Nozzle Throat (cm^2)	Plasma Generator Average Pressure (atm)	Plasma Generator Operating Time (s)	Magnet System Current (kA)	Channel Generated Power, (MW_e)
1	5-94-L	+35	73.48	44.5	8.45	16.4	12.18
2	48-89-L	+20	73.48	46.7	8.50	16.4	11.99
3	6-94-L	+ 2	80.00	35.2	10.24	14.1	9.00
4	6-94-L	+35	76.20*	44.7	8.24	16.4	12.34

* The larger cross section is a result of nozzle erosion.

On the basis of the analyses of the random test results, the following conclusions were made:

1) The performance parameters for the charges from both newly made batches (5-94-L and 6-94-L) are similar to each other. Because both batches were manufactured using identical raw materials and used the same technological procedures and equipment, this result was expected;

2) In Test No. 5 of the Acceptance Test Program in Russia, which was performed on 10 August 1994, lower pressure in the plasma generators with the OE-72 charges from the 48-89-L batch may be explained by their improper thermostating. Thus, the effective (final) thermostating temperature appeared to be slightly above 20°C;

3) At a thermostating temperature of +35°C, the performance parameters of the charges from the 5-94-L and the 6-94-L batches are close to those from the 48-89-L batch at the thermostating temperature of +20°C. In particular, as shown in Table 16, the plasma generator operation time at a thermostating temperature of +35°C was 8.24 s for the 6-94-L batch, and 8.45 s for the 5-94-L batch, and 8.5 s for the 48-89-L batch at a thermostating temperature of +20°C. As a consequence, the combustion flow rate, as well as the output power, is expected to be approximately the same for these three cases. Therefore, the results from the charges from the 5-94-L and 6-94-L batches in the maximum power mode are expected to be close to those for the Test No. 5 of the preliminary acceptance test program.

4) The preferable strategy for the Acceptance Tests in the United States was to use the 6-94-L batch for the maximum power mode of the Pamir-3U facility operation;

5) Because of the operation time obtained for the plasma generator with a charge from the 6-94-L batch with a nozzle throat area enlarged to 80 cm^2 and thermostated at a temperature of + 2°C, the pulse duration at the load is expected to be about 8.5 - 8.7 s, which is within the limits of the technical requirements; and

6) The operational ability of the OE-72 charges and the GP-77 cases manufactured for the Acceptance Tests in the United States was confirmed by the random firing tests that were performed.

4.2 MHD CHANNEL

4.2.1 Manufacturing

Figure 34 shows the MHD channel arrangement. The main constituents of the MHD channels are: inlet insert, case, strengthening shield, and flanges. All of the materials used for the channel manufacture were certified for high quality.

The inlet insert and flanges are made of special blanks that were subjected to mechanical treatment. The insert material is graphite; and the flange material is steel. After mechanical treatment of the insert, its outer surface was wound with glass cloth impregnated with a mineral binding. Then the cloth was dried, mechanically treated, and at last the finished insert was encapsulated at the inlet flange using epoxy resin.

The case is assembled from electrode and insulating walls using a special mandrel with a geometry similar to the geometry of the duct. The walls are made of mineral fiberglass reinforced plastic. They have a series of blind and through holes. At the inlet channel area, the blind holes are filled with ceramic modules that are sealed using mineral glue. At the working area of the electrode walls, electrodes that are made of square graphite plates with a central hole are encapsulated. Each electrode is fastened to the copper bus by a bushing, a steel stud, and a nut. While fastening each electrode to the bus, the transition electrode-bus resistance is measured using a microohmmeter. If the resistance value is beyond the specified limit, the fastening elements are to be strengthened.

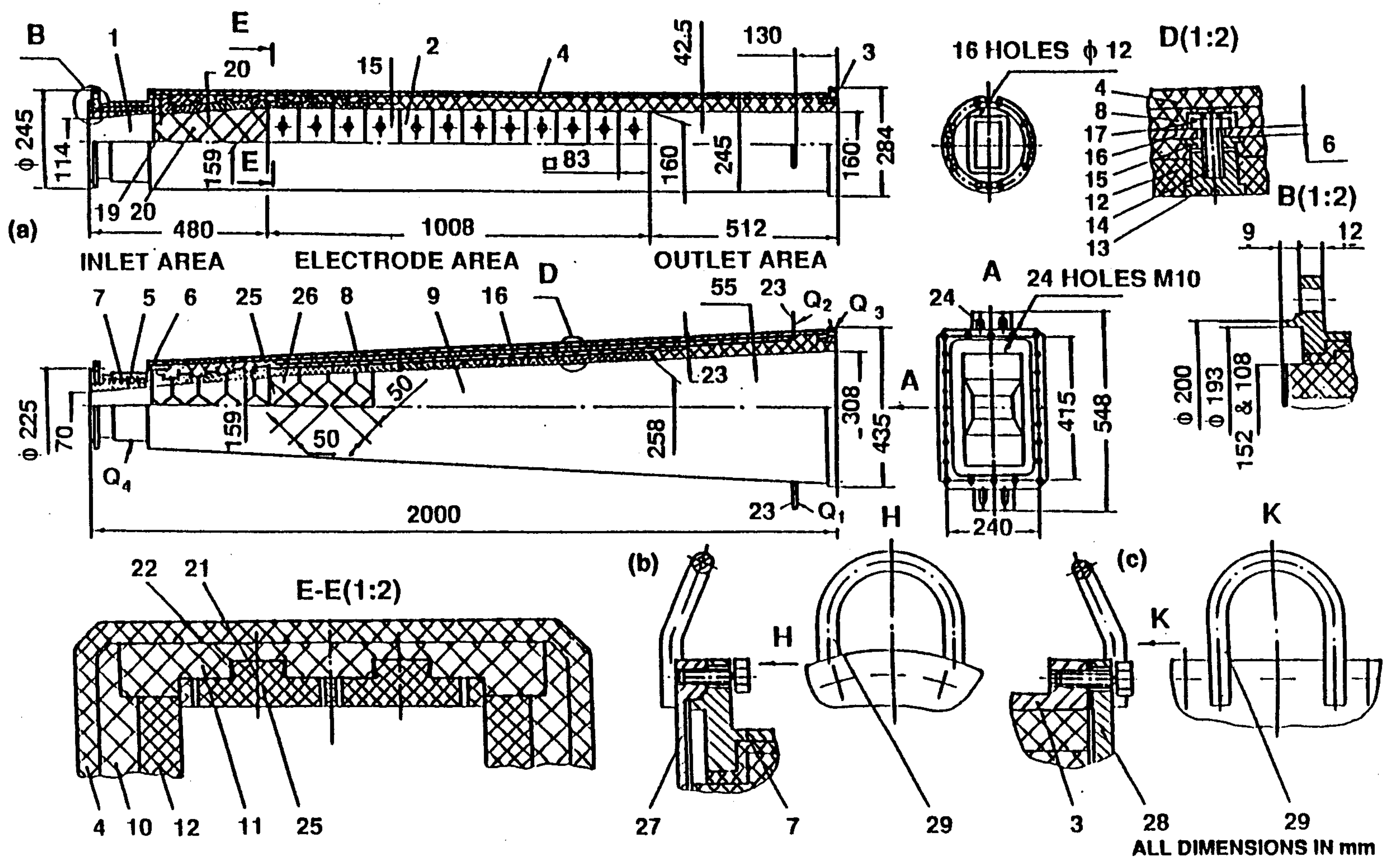
The assembled walls are glued to each other using high temperature mineral glue applied to the joined surfaces. Then, the glue is dried, and the assembled walls are encapsulated in glass cloth impregnated with an epoxy resin. After the epoxy resin is polymerized, the ends of the case are mechanically treated to fit the flanges. At last, the outlet flange is installed using a hermetic seal.

The strengthening shield is manufactured as follows. The assembled case is installed on a special mandrel with a winding tool, and is wound with glass cloth impregnated with an epoxy resin. Then, the case is removed from the tool and placed in a reduction press mold to give the strengthening shield the specified geometry. At last, the epoxy resin is polymerized under specified thermal conditions.

The MHD channel assembly ends with the installation of the inlet flange with the insert on the strengthened case. The inlet flange is hermetically sealed and also fastened by four screws. In order to improve the channel hermeticity, the areas of the flange-to-case connection, as well as the areas near the bus withdrawals, are wound with several additional layers of the glass cloth impregnated with epoxy resin. The process of the MHD channel manufacture is completed by removal of the technological mandrel, and execution of the technological tests.

4.2.2 Technological Tests

Along with manufacturing of the strengthening shield, a sample shield for testing mechanical parameters of the entire shield during the assembly stage is also manufactured. The sample shield mandrel is connected to the MHD channel mandrel, and the sample shield is wound simultaneously with the entire MHD channel shield using a unified winding process. Also, the sample shield drying is performed simultaneously with the drying of the entire shield, under the same pressure and temperature conditions. A series of sample specimens is made from the sample shield. The specimens, named the witness specimens, are tested to measure the physical and mechanical parameters of the shield.



A) MHD CHANNEL; B) TRANSPORT END CAP ON A FRONT FLANGE; C) TRANSPORT END CAP ON A BACK FLANGE.
1 - INLET INSERT WITH A FLANGE; 2 - DUCT; 3 - BACK FLANGE; 4 - LOAD BEARING SHELL; 5 - GRAPHITE INSERT;
6 - HEAT PROTECTION; 7 - FRONT FLANGE; 8 - ELECTRODE WALL; 9 - INSULATING WALL; 10, 11 - CASE PARTS OF ELECTRODE AND INSULATING WALLS ACCORDINGLY; 12 - ELECTRODE; 13 - BUSHING; 14 - STUD BOLT; 15 - NUT; 16 - CURRENT PICK-OFF BUS; 17 - NUT; 18 -COVER; 19, 20 - CERAMIC MODULES; 21 - MODULE TAIL; 22 - SEAT FOR TAIL; 23 - CURRENT LEAD; 24 - GROOVE; 25, 26 - CERAMIC MODULES; 27,28 - TRANSPORT END CAPS; 29 - SHACKL

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Figure 34 MHD Channel Arrangement

The physical and mechanical parameters, which are measured, are as follows: bending strength, elasticity modulus in bending, and shear strength. The witness specimen sizes are as follows (mm):

- for bending tests $80 \times (10 \pm 5) \times (4 \pm 2)$
- for shear tests $60 \times \left(15\,^{+0.0}_{-0.2}\right) \times \left(10^{+0}_{-2}\right)$

The quantity of witness specimens to be tested from a single lot of the material should be no less than five for every direction chosen to have its mechanical properties measured.

The bending tests are performed in a bending machine providing load measurements with an accuracy of 1%. The bending strength is to be no less than 7,000 kg_f/cm^2. The elasticity bending modulus is taken to be a ratio of the strength increment to the deformation increment. The elasticity bending modulus is to be no less than 0.3×10^6 kg_f/cm^2.

The tests of the witness specimens for the shear strength along a layer are made in a rupture machine or in a universal testing machine. The test involves applying an incrementally increasing load to the specimen under constant temperature, maintaining constant velocity of the machine clamps. The measured value is the value of the maximum load that causes the specimen to shear along the layers. The shear strength is to be not less than 300 kg_f/cm^2.

The channel test for hermeticity is executed by applying a soap. The channel faces are plugged by end-pieces, with one of the end pieces having a pipe. Through that pipe, compressed air or nitrogen is dispensed inside the channel under a gage pressure of 0.075 to 0.1 MPa (0.75 atm) measured by a reference manometer. Then, external surfaces of the channel are coated with a soap emulsion. Special attention is given to the power take-off region, as well as to the areas where flanges join the glass cloth windings. In the locations with leaks, bubbles, which grow in size, are formed.

In order to ensure air-tight integrity, the locations with leaks are thoroughly cleaned from the soap, then degreased and dried. A vacuum pump is connected to the pipe to produce a reduced pressure inside the channel compatible with the reduced pressure of the closed system without the channel, but not less than 0.6 atm. Then, a compound with 10% added dibutylphtalate is applied at the locations of the leakage. The compound is continuously applied to the locations of leakages for one half hour. The pump is then disconnected, and the surplus emulsion is removed. After the compound is allowed to polymerize for 24 hours at 20°C, the hermeticity test is repeated.

The channel electrical tests are performed after the hermeticity test. The electrical tests involve: insulation resistance measurements between the channel buses and between the buses and the flanges; the insulation resistance is to be no less than 4 MΩ; and reassurance of the insulation strength between the channel buses and between the buses and the flanges, when a 5 kV voltage is applied.

The data certifying control of the channel geometry and control of the tests are recorded on the channel certificate.

4.3 MAGNET SYSTEM

The magnet system consists of four round electromagnets. The general view of the magnet is shown in Figure 35. Each electromagnet, which is shown in Figure 36, consists of an ellipsoid plane coil and two outer and one inner inserts fastened by a round force binding. The inserts and the binding are made of glass-reinforced plastic, having glass cloth impregnated with an epoxy compound as a base, which is then subjected to pressure and temperature polymerization.

The coil consists of two sections. Each section consists of a copper bus with a cross-section of 10 x 25 mm^2, which is wound on special tooling equipment. The equipment allows for the application of turn and case insulation and its impregnation with an epoxy compound, followed by pressure and temperature polymerization of the turn insulation. After each section is manufactured, the turn and case insulation is visually inspected for quality to ensure the absence of breakages, folds, exfoliations, and local variations of rated thickness. After the visual inspection is complete, the section is tested for: the absence of short-circuited turns; the electrical strength of the insulation between turns by applying an AC voltage of 5 kV for 5 s; and the electrical strength of the case insulation by applying a DC voltage of 5 kV for 1 minute.

When the electromagnet is assembled, it is tested for: the insulation strength between one electromagnet terminal and the binding studs, using a megaohmmeter, by applying 2.5 kV. The resistance should not be less than 500 MΩ; and electrical insulation strength between one electromagnet terminal and the binding studs by applying a DC voltage of 5 kV for 1 minute.

After the magnet system has passed the tests for electrical strength and insulation resistance is installed on the frame, the magnet system inductance and ohmic resistance were measured. The results were recorded in the certificate IM1-3.01.10.000PC .

4.4 ELECTRIC EQUIPMENT UNIT

A general view of the electrical equipment unit (EEU) and its main parts is presented in Figure 37. The main element of the EEU is a framework, welded from steel angles and channels that has terminals for connection of grounding cables as well as fixtures for hoisting.

All units are mounted on the framework with bolts and then grounded. The inside-unit mounting is made by plane copper buses that are installed and fixed on the glass-reinforced plastic supports. The buses have detachable joints and are fixed to the units by bolts.

After assembly, the EEU is tested for electrical strength, insulation resistance, and joint resistances. The results are recorded in the certificate IM1-3.02.00.000 PC.

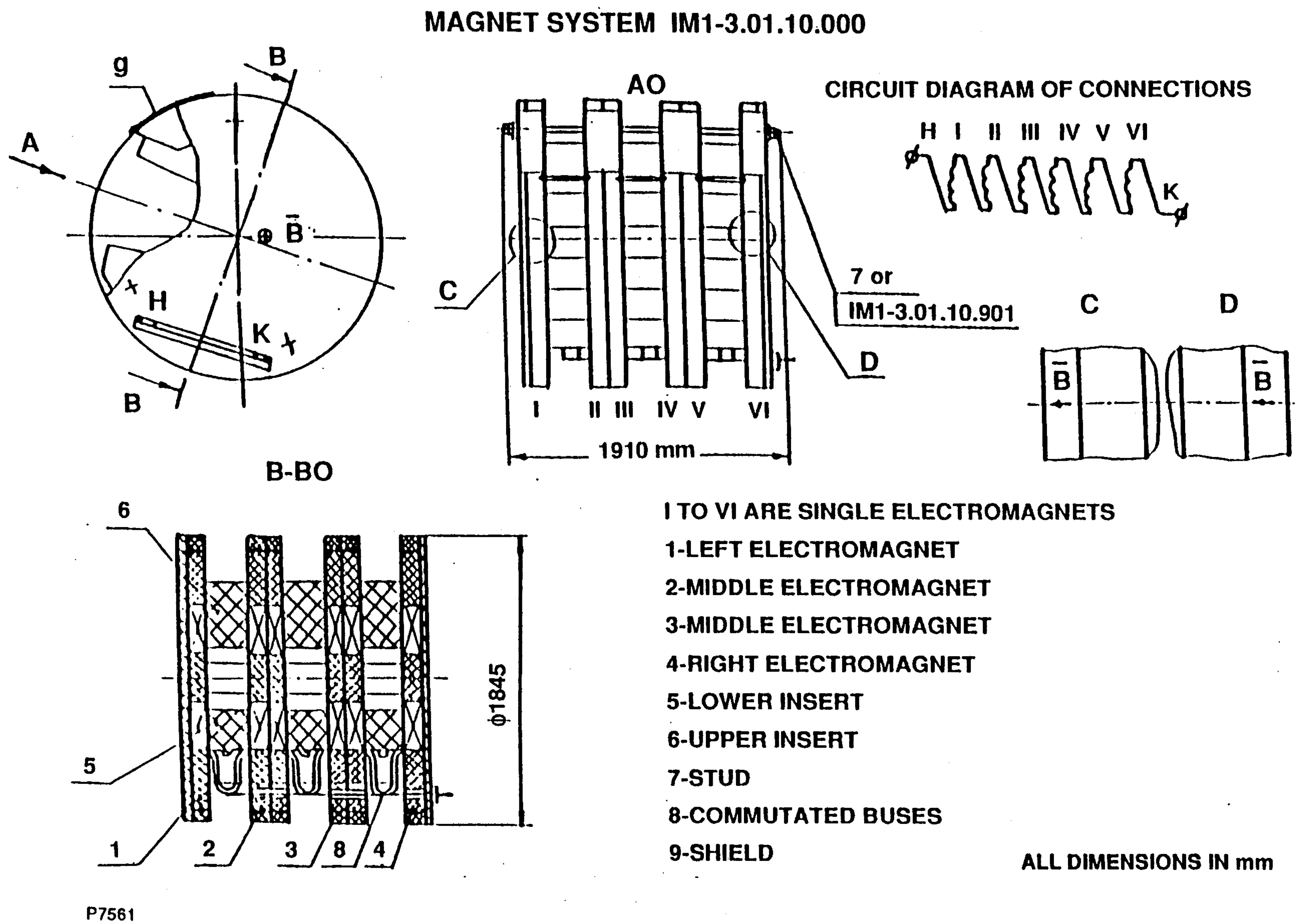


Figure 35 Pamir-3U Magnet System

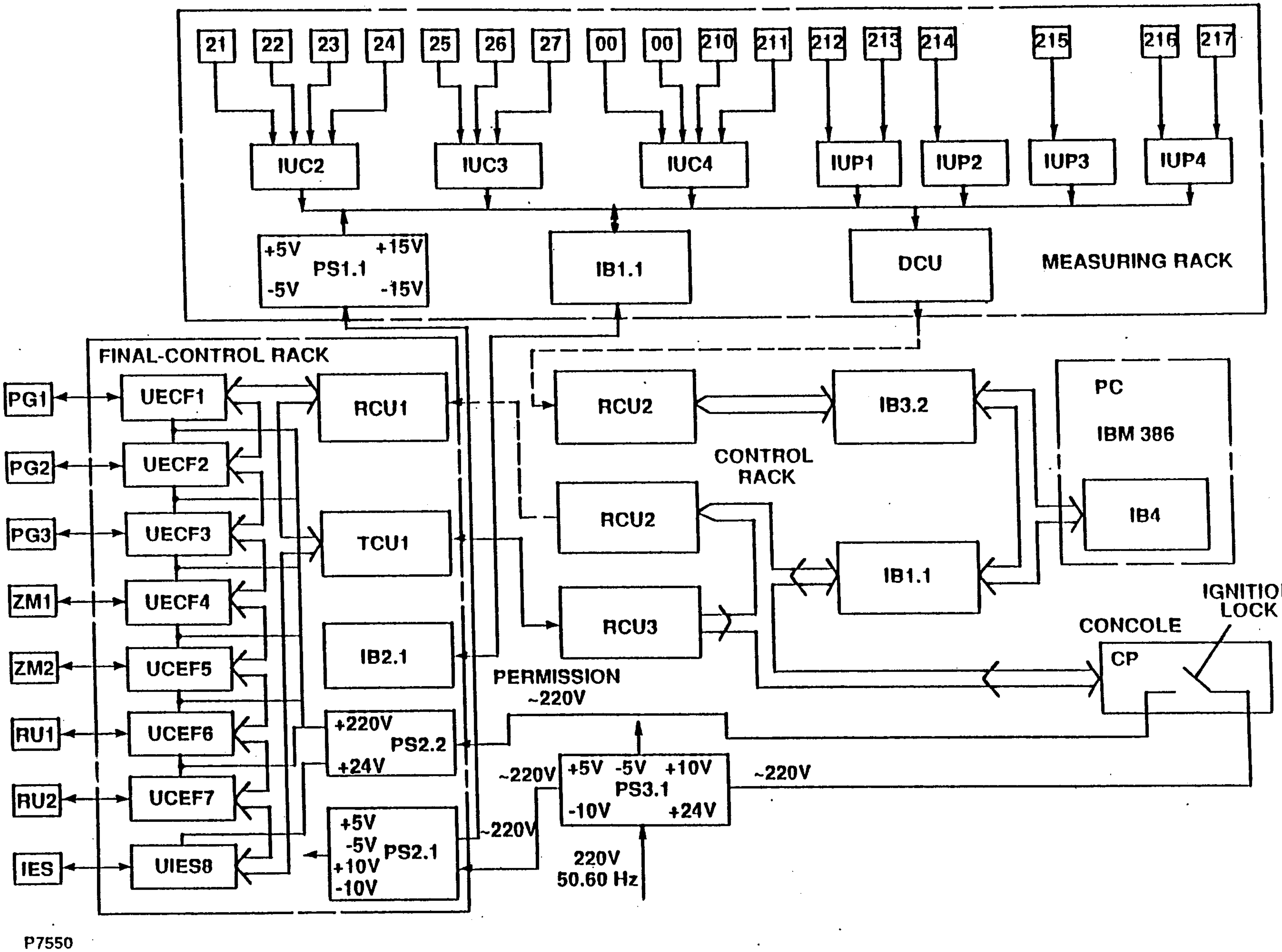
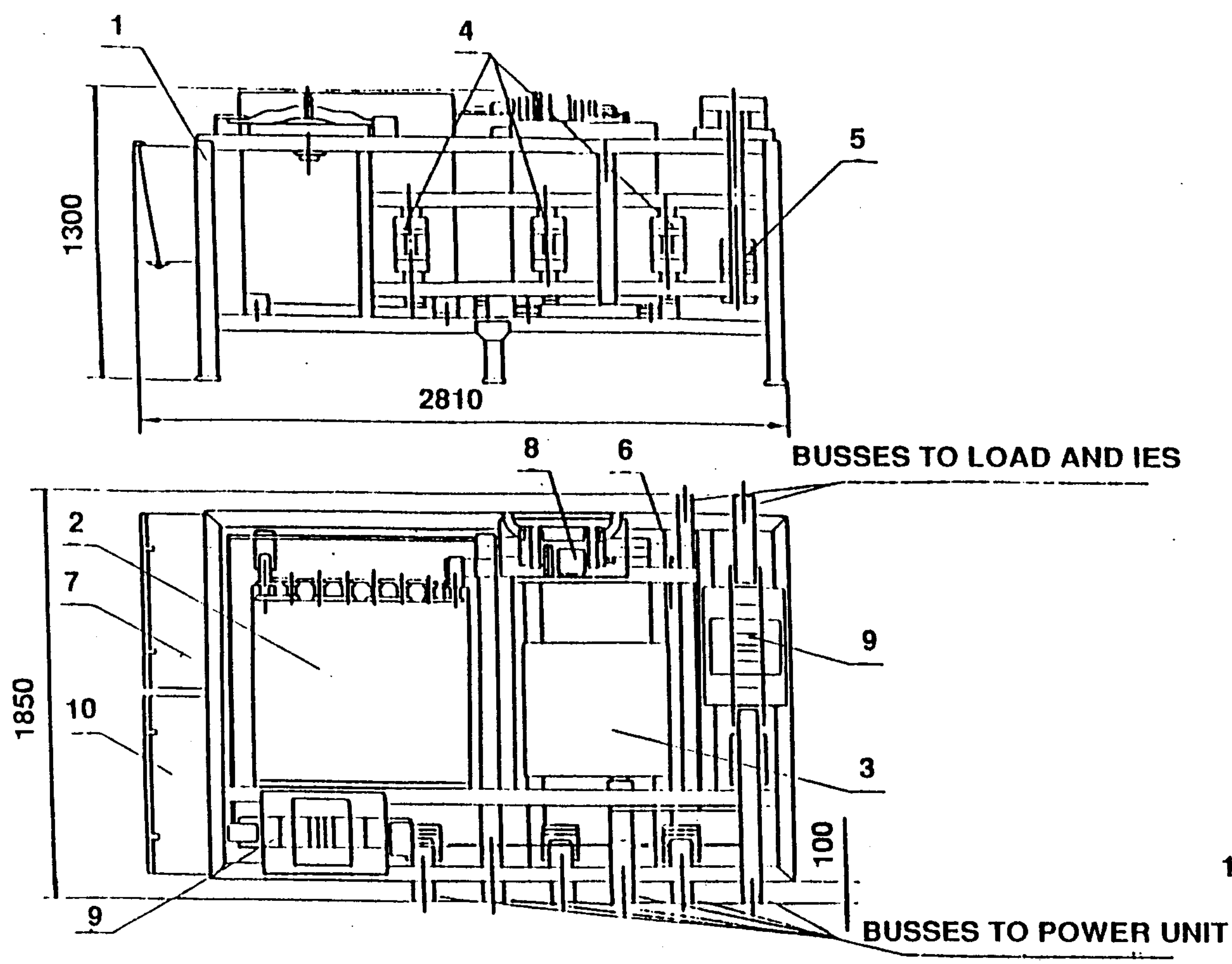


Figure 36 Electromagnet Assembly

ELECTRICAL EQUIPMENT UNIT IM1-3.02.00.000



1-FRAME WORK;
2-BALLAST RESISTANCE;
3-PROTECTION UNIT;
4-SHUNT UNIT (TM, TK1, TK2);
5-SHUNT UNIT (TH);
6-SHUNT UNIT (THB);
7-CONTROL UNIT;
8-BREAKER;
9-CONTACTOR;
10-MEASURING UNIT;

ALL DIMENSIONS IN mm

P7559

Figure 37 Electrical Equipment Unit

4.5 INITIAL EXCITATION SYSTEM

The Initial Excitation System (IES) cabinet construction was developed at IVTAN, but the cabinet was produced by another manufacturer under IVTAN supervision.

The storage batteries, power thyristors, load resistors, electrical heaters, shunts, the automatic switch, and accessories for the battery charger, the potential isolator, and the control board were purchased. The control board, battery charger, the potential isolator, and the current commutator were designed, manufactured, and/or modified at IVTAN. The IES electrical mounting, assembling, adjustment, and tests for the dummy load were conducted at IVTAN. Tests for the real load during cold and firing runs were conducted in Russia at the Geodesiya Research Center. The IES operational experience in Russia and in the United States demonstrated its high reliability and easy maintenance.

The IES with these particular storage batteries has the following disadvantage: the initial preparation for operation and also during the preparation for re-starting operation after a long interval between operations is a labor intensive operation. An alternative that could be used would be a dc power supply. However, this would not allow for the desired remote operation. Thus, batteries should be maintained in the IES to provide the maximum operational flexibility.

4.6 CONTROL, MEASURING, MONITORING AND RECORDING SYSTEM

During the Control, Measuring, Monitoring and Recording System (CMMRS) design and manufacture, only certified accessories and materials were used. The delivery set includes the certificates for all purchased articles that are used in the CMMRS as a complete functional unit.

The following purchased articles have certificates in the delivered set: 386 PC computer ; Digital Data Transmission Device "Electronica MS4101"; Analog Data Collection Device "Electronica MS8201"; and pressure transducers MD 60, and MD 80.

The non-standard elements were designed and manufactured with the use of certified accessories and materials. The following non-standard elements were manufactured during the CMMRS design: power transformer RAN 36.08.05.01.00; pulse transformer RAN 36.08.01.01.00; isolation transformer RAN 36.06.11.01.00; isolation transformer RAN 36.06.11.02.00; and isolation transformer RAN 36.06.11.03.00. During their manufacture, the following materials were used: copper winding wire PETV TU16-705.110-79; fluoroplastic tube F-4D, the State Standard 2205676; and varnished fabric LES-0.15, the State Standard 5937-81. The transformers were tested for agreement with the imposed requirements on them.

The electrotechnical fiber-glass plastic FS-2N-50G-2,0, the State Standard 10316-78 was used in manufacturing the printed-circuit boards. The printed-circuit boards were manufactured on standard technological equipment, and all of the requirements of the technological process were satisfied.

Structural dimensions specified in "EVROSTANDARD" were used as a basis for dimensions and construction of the printed-circuit boards. The board dimensions are 233 x 180 mm^2.

The necessary mounting process during manufacture of the printed circuit boards and of the CMMRS units was performed at the IVTAN production facilities. All of the mounting work was performed according to the standard document requirements.

In order to increase the insulation resistance of the printed circuit boards, the remaining flux was removed from the surfaces after mounting. This removal was performed by washing the printed-circuit boards with ethyl alcohol.

The following materials were used for manufacturing the elements and units of the mechanical construction: aluminum sheet of $AlMg_2$ and D16 type, the State Standard 4787-74; steel of 10 and 20 type, the State Standard 1050-88; and steel angle, the State Standard 13737-80.

The "CAMAC" construction elements were used in the block and unit construction. The block dimensions are: Measuring Rack - 450 x 360 x 550 mm^3 (length, width, height); Final-Control Rack - 450 x 360 x 550 mm^3; Control Rack - 450 x 360 x 250 mm^3; and Console Panel - 300 x 250 x 150 mm^3. The Measuring and Final-Control Racks have individual safety boxes.

The units are constructed in the form of easily detachable modules. There are built-in connectors on the back panels of the power supply units and ignition units. Several SNO 64 type connectors are on the back panels of the other units.

The interior rack mounting is performed by mounting wire between connectors installed on the rack back panels. The connectors intended for external cable connection, except for the fiber-optic cables, are installed on the front panel. The fiber-optic cables are connected directly to the Receiver-Transmitter units. All control device indication, and safety device holders are installed on the front unit panels.

The results of the high voltage tests of the CMMRS detail insulation are given below. The insulation resistance was measured by a M4100/5 megaohmmeter. The insulation strength was measured by a UPU-10 device. The following details were tested:

1. Transformers (9 pieces) of the Ignition Units modules; the test results were: the insulation resistance between the windings and the cores of all transformers was more than 500 MΩ; and leakage current was absent during a voltage increase up to 9 kV across each winding.

2. Transformers (20 pieces) of the Galvanic Isolation amplifiers; the test results were: the insulation resistance between the windings and the cores of all transformers was more than 500 MΩ; and leakage current was absent during a voltage increase up to 7 kV across each winding. In some transformers, the leakage current was from 4 to 6 μA at voltage of 9 kV.

3. The CMMRS measuring and ignition and pressure transducer cables (17 pieces); the measurements were taken on the metal sheet of 1 x 2 m^2; the test results were: insulation resistance (between the strands and between the strands and the sheet) of all cables was more than 500 MΩ; and leakage current was absent during a voltage increase up to 9 kV across all strands together, with reference to the sheet.

According to the tests results, the articles were considered to be serviceable in the CMMRS of the Pamir-3U MHD facility.

5.0 OPERATION OF THE PAMIR-3U FACILITY

5.1 PRINCIPLES OF OPERATION

5.1.1 Introduction

The principal view of the MHD facility is shown in Figure 38. The schematic circuit diagram and the circuit diagram of the electrical connections for the power components are shown in Figure 39 and Figure 40, respectively.

The MHD facility is transported to its operation location in a disassembled form. The power unit is installed on a specially prepared site. The Initial Excitation System (IES), the electrical equipment unit, and the load are installed near the power unit. A control desk, a computer and the other Control, Measuring, Monitoring, and Recording System (CMMRS) units are placed in a shelter providing for operator safety during the MHD facility firing run.

The units and systems of the MHD facility are connected together by buses and cables. All high voltage power circuits of the MHD facility are insulated from the grounded equipment cases, and isolated from low voltage circuits of the CMMRS and from the primary power source that is at an operating direct voltage of 2.5 kV. The cases of the MHD facility components and the minus bus in the electrical equipment unit are connected with a protective grounding device, of which the grounding electrode resistance is no more than 10 Ω.

The location of the current transducers (shunts) and the connection points for voltage transducers are shown in Figure 39. The pressure transducers are installed in each plasma generator.

5.1.2 Operation

The facility components are electrically connected and function according to a preset logic for the self-exciting MHD generator designed for operation with a resistive load. The MHD generator uses the chemical energy of a special propellant containing ionized seed.

During propellant combustion in the plasma generator chamber, a plasma is generated, which then enters the MHD channel. An initial excitation system charges the magnet system, and in so doing, an initial magnetic field is generated in the power producing sections of the MHD channels. An electromotive force (emf) is generated at the MHD channel electrodes as a result of the interaction between the magnetic field and the flowing plasma. The MHD facility parameters are calculated so that the self-excitation condition is met; that is, at a self-excitation current, the generated emf is more than the voltage drop in the excitation circuit. The MHD generator power output increases, and the magnet system current begins to increase. When the preset current is reached, the load is connected, and a ballast resistance is connected to the excitation circuit to limit the current in the magnet system.

Transducer signals are used for formation of control commands and for continuous recording of the main MHD facility parameters during its operation. The passage of commands to the squibs in the plasma generator and in the contactors, to the electric blasting caps in the breakers

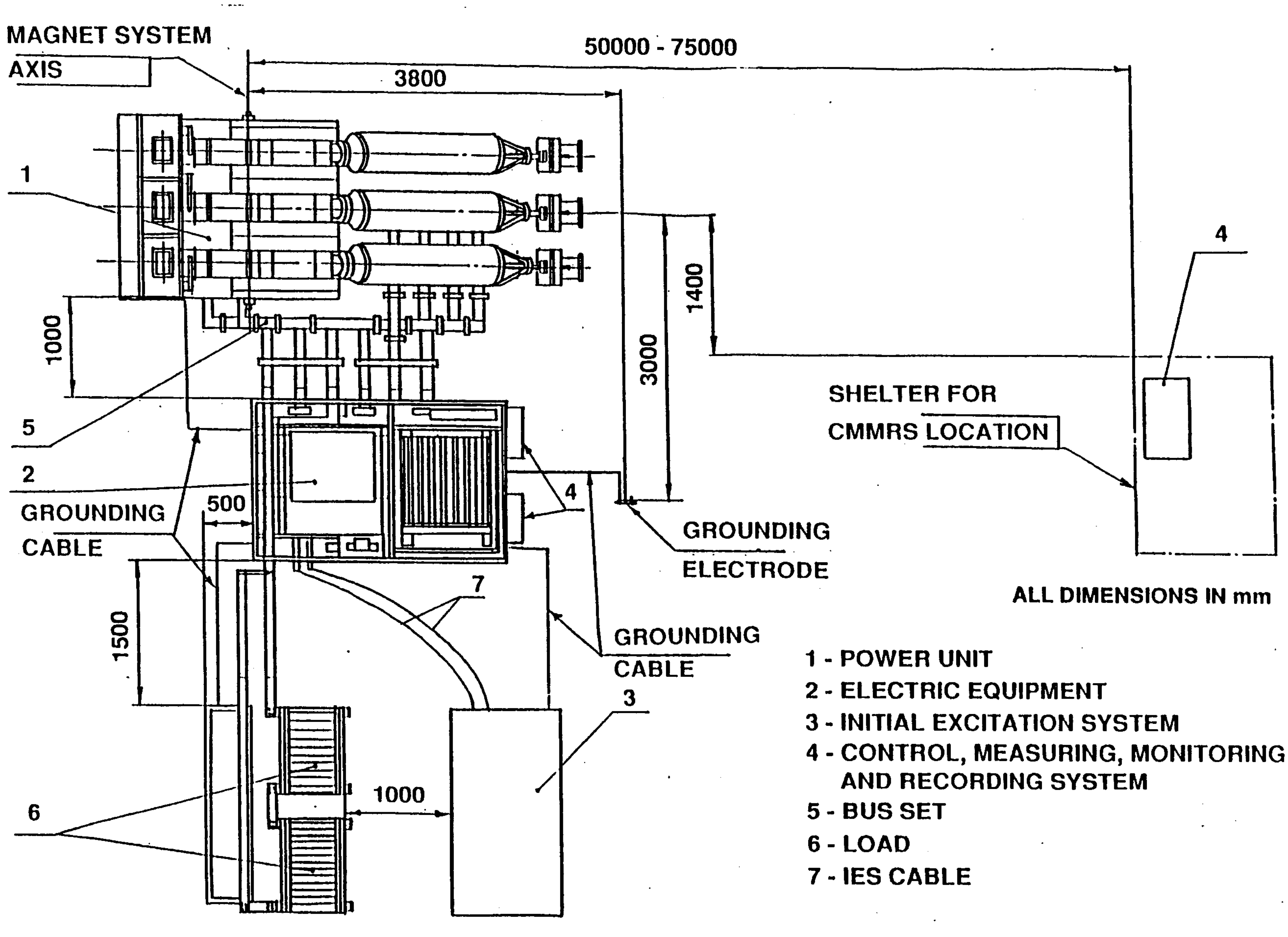
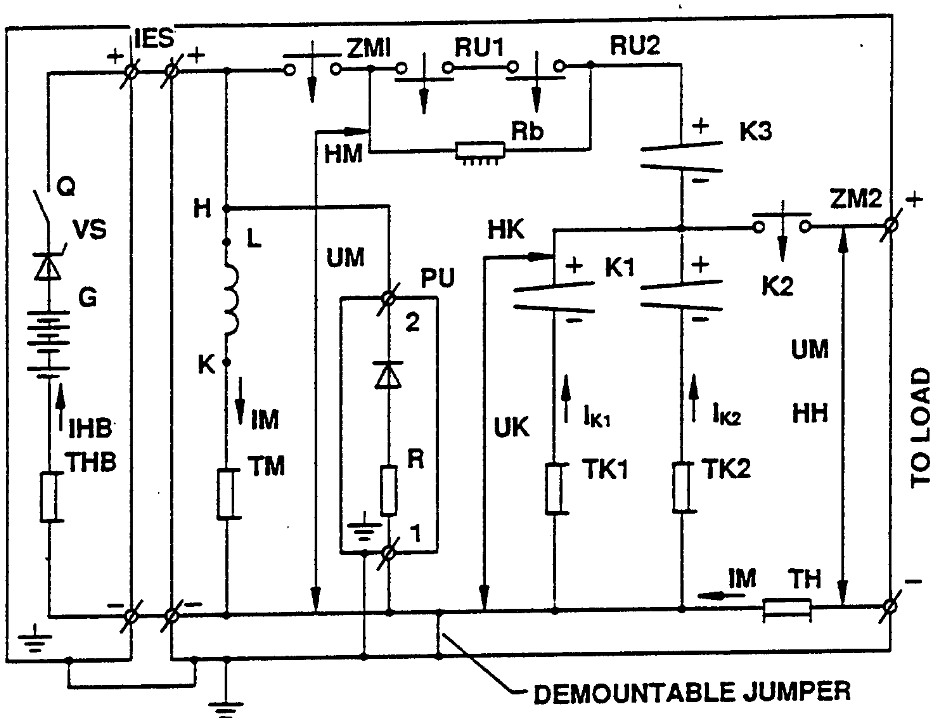


Figure 38 Pamir-3U MHD Facility



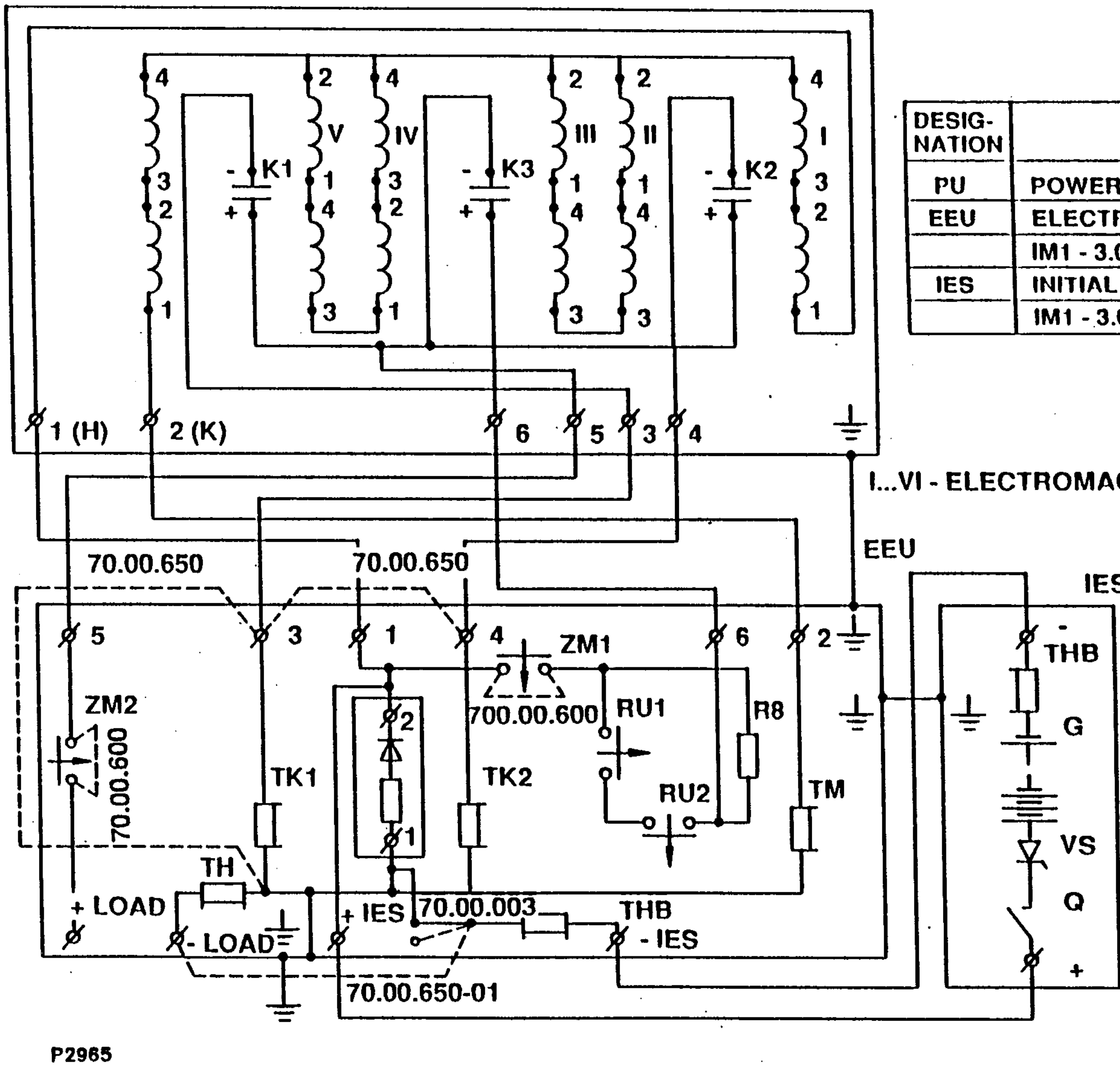
TM, TK1, TK2, TH, THB-CURRENT TRANSDUCERS

HM, HK, HH - CONNECTION POINTS OF VOLTAGE TRANSDUCERS

DESIG-NATION	NAME	NUM-BER	NOTE
IES	INITIAL EXCITATION SYSTEM		
	IM1 - 3.03.00.000	1	
K1 to K3	UNIT IM - 112-5.00.000	3	MHD CHANNEL
L	MAGNET SYSTEM IM1-3.01.10.000	1	
RU1, RU2	BREAKER IM - 115-VP-1.00.000	2	
ZM1, ZM2	CONTACTOR X-8F 01.05.000	2	
PU	PROTECTION UNIT IM1 -3.02.00.500	1	R = 0.1Ω
R6	BALLAST RESISTANCE		
	IM1 - 051M.01.05.000	1	R_{MAX} = 40 mΩ

P2978

Figure 39 Electrical Circuit Schematic Diagram



I...VI - ELECTROMAGNET COILS OF MAGNET SYSTEM

——— "HOT" SHOT
------- "COLD SHOT"

DESIG-NATION	NAME	NUM-BER	NOTE
PU	POWER UNIT IM1 - 3.01.00.000	1	
EEU	ELECTRIC EQUIPMENT UNIT	1	
	IM1 - 3.02.00.000		
IES	INITIAL EXCITATION SYSTEM	1	
	IM1 - 3.03.00.000		

Figure 40 Circuit Diagram of the Electrical Connections

and to the IES electrical commutators (thyristor switches and automatic breaker). is recorded immediately.

The results of the analysis of the recorded parameters and commands allow for estimates of the quality of the MHD facility operation, for adjustments to the ballast resistance, and for an assessment of the performance between firing runs, as well as for detection of the causes of possible malfunctions.

The total process of the MHD facility operation (during one firing run) can be divided in time into the following stages: initial excitation stage; self-excitation stage; stage of operation at the load; and stage of dissipation of the power accumulated in the magnet system. Functional electrical diagrams for the considered operational stages are shown in Figures 41 to 44. On the diagrams presented, the limiting currents and their directions are shown.

5.1.3 Cold Run Checkout Tests

The MHD facility design allows for performance of the so called cold runs before the squibs are installed in the plasma generators and in the contactors, and before the electric blasting caps are installed in the breakers. The MHD facility cold run allows for estimates of the readiness of the units and systems for the firing run. In the process of the cold run, the THB initial excitation current and the presence of the TH, TM, TK1, and TK2 currents shown in Figure 40, as well as the passage of commands are recorded. The cold run can also be performed without the IES turned on. In this case, only the passage of commands is recorded.

5.2 ASSEMBLY OF THE MHD POWER SYSTEM ON THE TEST SITE

5.2.1 Installation at the Test Site

The installation of the MHD Facility at the location of its operation is performed according to the Operation Manual IM1-3.00.00.000 OM[1] in the following sequence:

1) the base plate IM1-3.08.00.000 is installed and attached to the embedded parts of the stand or the test site;

2) the magnet system frame is installed, adjusted, and attached to the base plate;

3) the buses are installed and attached to the base plate;

4) the magnet system is installed on the frame and attached to it;

5) the buses are installed and fixed on the frame and the magnet system;

6) the rests and supports for the plasma generators are installed and fixed on the base plate;

7) the protective shields are installed on the frame and fixed;

8) the bus unit that is designed for commutation of the power unit buses with the buses of the electrical equipment unit is installed;

9) the electrical equipment unit is installed and commutated by the bus unit with the power unit buses;

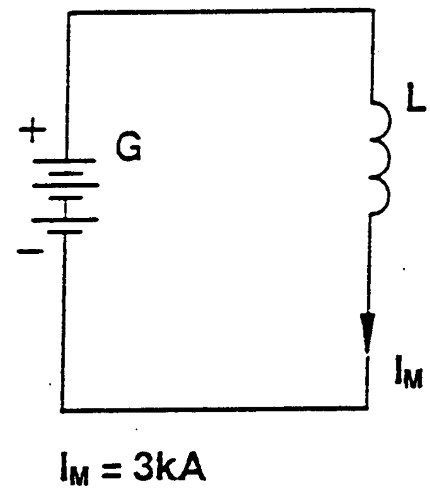


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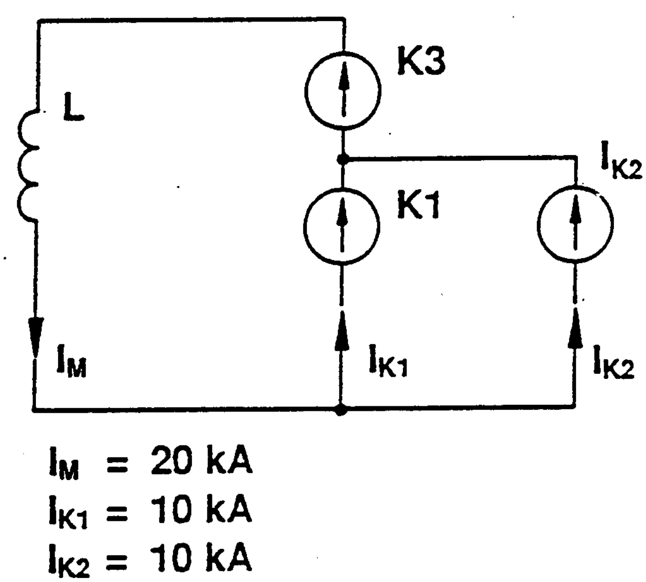
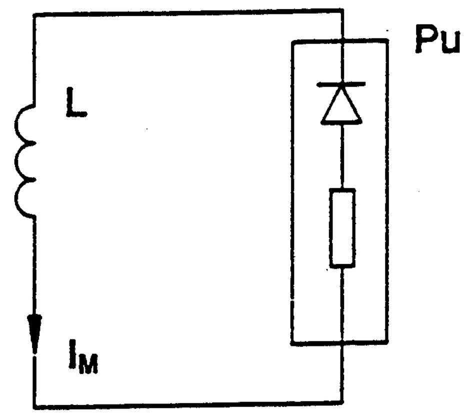
Figure 41 Functional Circuit Diagram at the Initial Excitation Stage



P2977-1

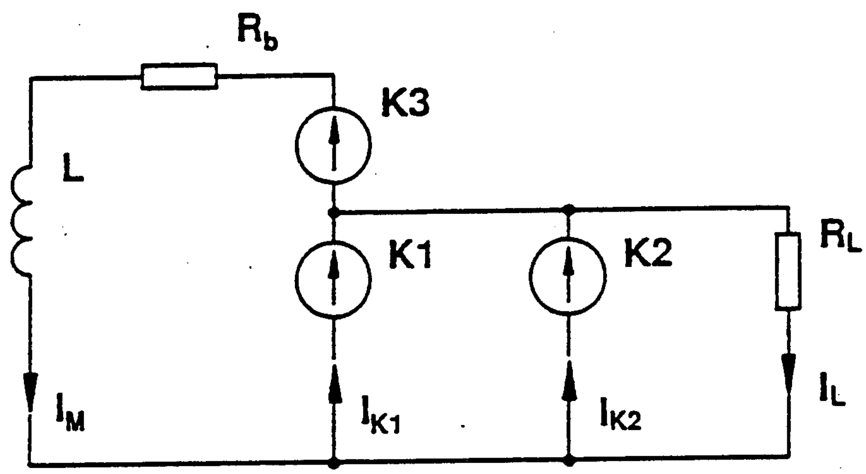
Figure 42 Functional Circuit Diagram of the Self-Excitation Stage



$I_M = 20$ kA

P2977-3

Figure 43 Functional Circuit Diagram of the Load Operation Stage



$I_M = 20$ kA
$I_{K1} = 28$ kA
$I_{K2} = 28$ kA
$I_L = 36$ kA
$R_L = 15$ mΩ
$R_b = 0$ to 40 mΩ

P2977-2

Figure 44 Functional Circuit Diagram of the Stage after MHD Channel Operation

10) the dummy load is installed and connected to the electrical equipment unit;

11) the initial excitation system is installed and connected by power cables to the electrical equipment unit; the IES grounding is connected to the electrical equipment unit case;

12) two units of the CMMRS are installed on the electrical equipment unit, and the CMMRS measuring cables are installed and connected to the transducers;

13) the CMMRS units are commutated by power, measuring, and control cables; and

14) the grounding cable is connected to the grounding device.

5.2.2 Firing Run Preparations

The following stage of the MHD facility assembly is performed during preparation for the firing run according to the Operation Manual IM1-3.00.00.000 OM[1], in the following sequence:

1) according to the firing run plan the necessary commutations in the electrical equipment unit and the ballast resistance are performed; if necessary, the load and ballast resistances are checked by a microohmmeter or by a similar device; two contactors and two breakers are prepared;

2) in the spaces between the electrical magnets of the magnet system, three plasma generator assemblies with MHD channels and stops are installed; the plasma generators are loaded, assembled, and thermostated previously, according to the Specifications and Operating Instructions GP77.TO[1], see Figure 45;

3) the MHD channels are connected to the buses of the electrical equipment unit;

4) in the spaces between the electrical magnets of the magnet system, three inserts are sequentially installed;

5) the electrical magnets are bound and fixed by a stud;

6) three protective shields are installed at the outlet flanges of the MHD channels;

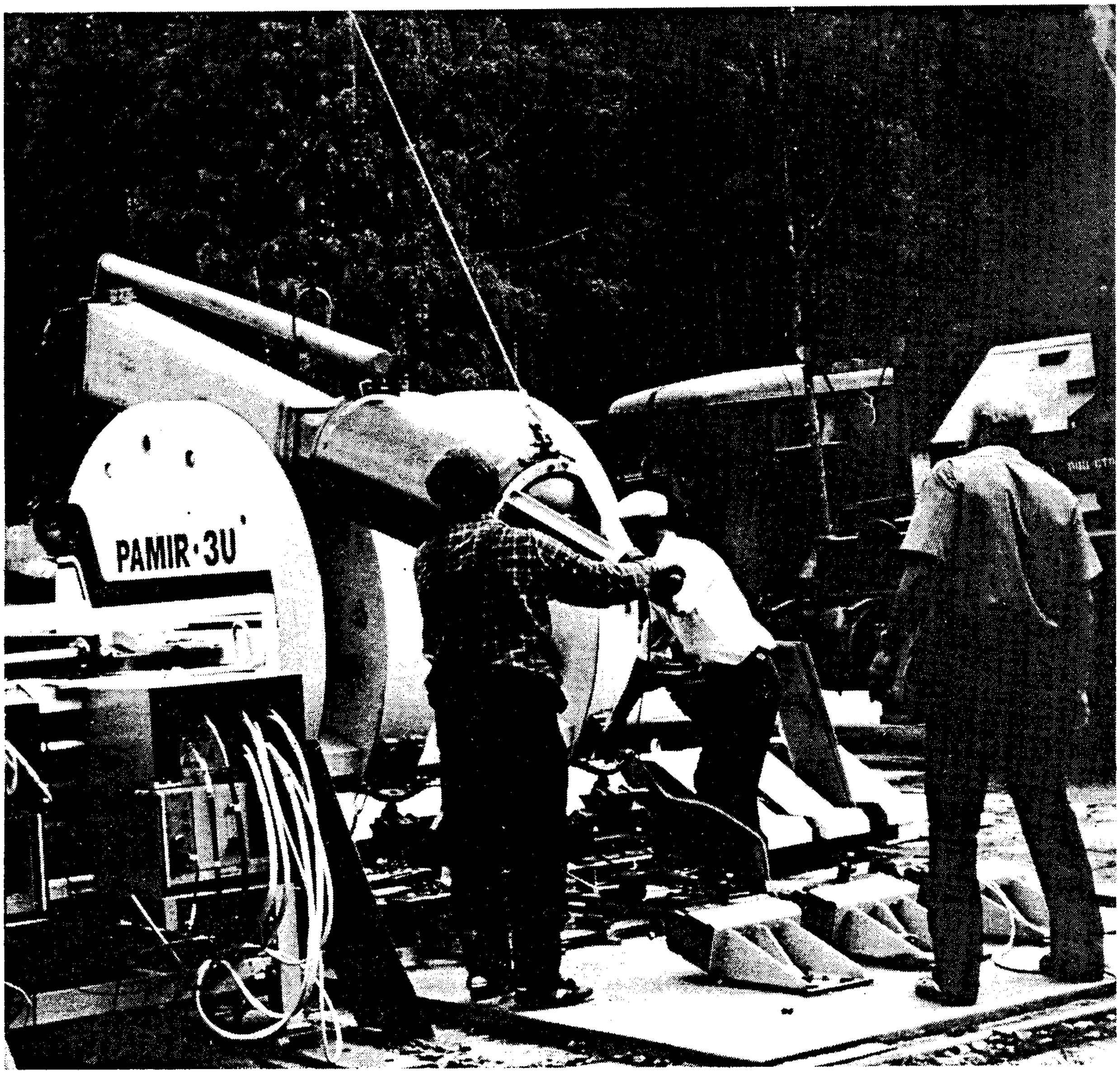
7) pressure transducers are installed in the plasma generator cases, one for each plasma generator, and the measuring cables are connected to the pressure transducers, see Figure 46;

8) the current conductors are installed into the breakers; and

9) the squibs are installed in the plasma generators and in the connectors; the ignition cables are connected to the squibs and to the ignition modules of the CMMRS;

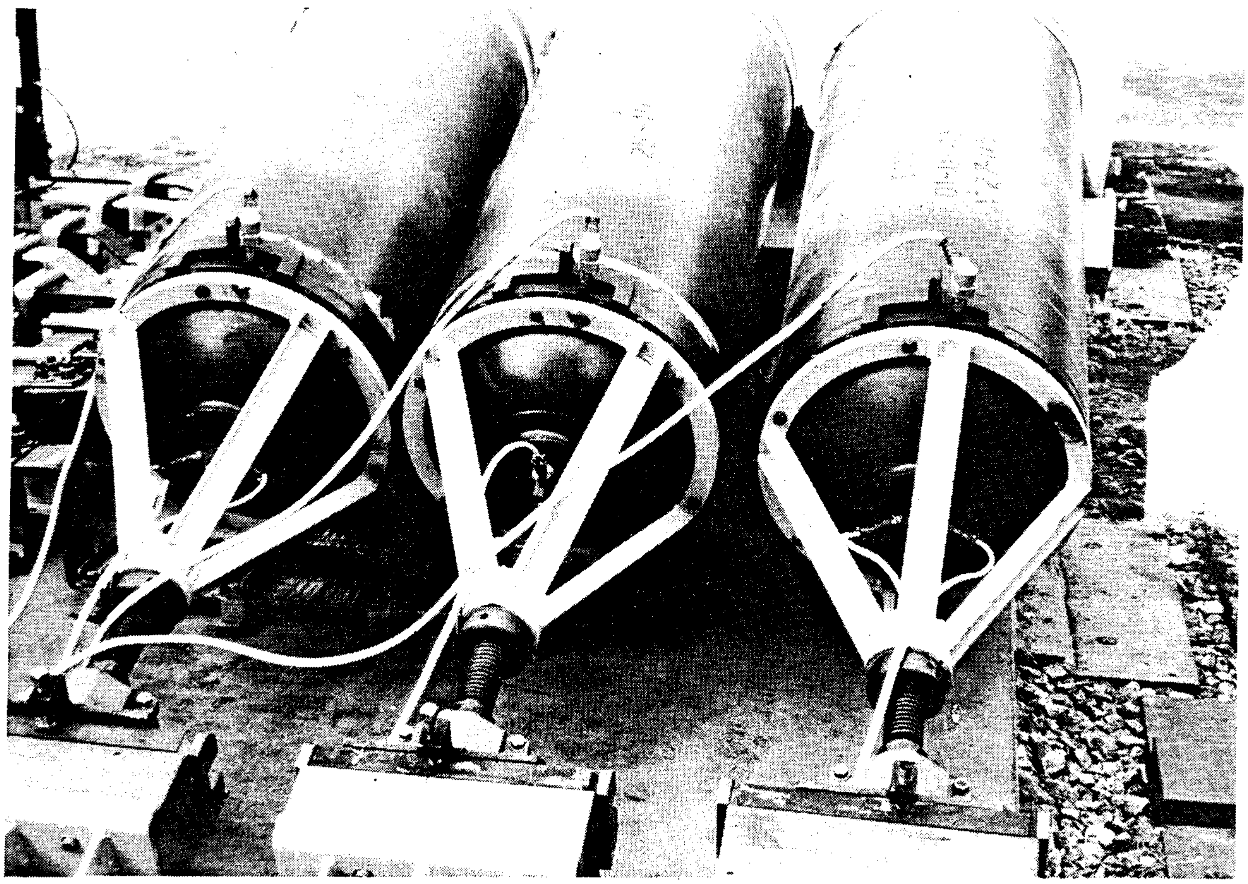
Note: The MHD channels and the protective shields may be installed before Step No. 1. In this case, the installation of the plasma generators is performed just before the firing run.

At this point the MHD facility assembly is complete.



P7613

Figure 45 Installation of the Plasma Generator and MHD Channel in the Pamir-3U Facility



P7612

Figure 46 Plasma Generator with the Pressure Transducers and Squibs Installed

5.3 CHECK-OUT

5.3.1 Electrical Equipment Unit Check-out

The following tests, check-outs and control measurements are performed on the electrical equipment unit:

1) visual inspection for the correct electrical connections according to the circuit diagram;

2) measurement of the grounding device resistance before or during mounting the MHD facility at the test site;

3) measurement of the initial excitation circuit resistance; usually performed one time after the MHD facility is mounted at the test site;

4) check-out of the insulation resistance using a megaohmmeter of 2.5 kV voltage, and check-out of the insulation electrical strength by applying a DC voltage of 5 kV for 1 min between the circuits having different potential; the insulation resistance shall not be less than 20 MΩ; these procedures are made before performing the set of firing runs;

5) check-out of the insulation resistance using a megaohmmeter by applying 2.5 kV voltage, and check-out of the insulation electrical strength by applying a DC voltage of 5 kV between the conductive parts of the circuit and the grounding device; the measured insulation resistance shall not be less than 10 MΩ; these procedures are performed before each firing run; and

6) check-out of the insulation resistance using a megaohmmeter by applying 2.5 kV voltage, and check-out of the insulation electrical strength by applying a DC voltage of 5 kV between the rests, supports and the grounding device; the measured insulation resistance shall not be less than 50 MΩ; these procedures are performed before the set of firing runs.

5.3.2 Control, Measuring, Monitoring, and Recording System Check-out

Check-out of the CMMRS operation ability is performed by repeatedly running the computer code TEST FCR.EXE.

5.3.3 Initial Excitation System Check-out

The primary readiness of the IES is checked by examining the results of measuring and correcting, if necessary, the density of the electrolyte in the storage cells and by measuring the voltage at each of the five parallel branches of the storage battery after charging. Finally, the IES readiness is tested during the first cold run on the results of the IES current measurement and on the operation of the commutators.

5.4 COLD RUN TESTS

For performance of the cold run, the connections shown in Figure 40 in the electrical equipment unit are made. The IES and CMMRS are prepared for operation and, in so doing, an indication of their readiness appears on the control desk.

By pressing the "START" button on the control desk, or according to a preset time, or in response to an outside signal, a KPHB command is fed to turn on the VS thyristor switches of the IES that power the magnet system coil along the circuit: "+" IES, L, TM, TK1, TK2 shunts connected in parallel, TH, "-" LOAD, "-" IES (the TH current flows in a backward direction). Subsequently, the MHD facility operates in an automatic control mode (as if running a regular test), see Figures 39 and 47.

The current of 2.8 ± 0.2 kA in the circuit being considered is set within 1.6 s. After 1.7 to 1.8 s, the KQ command to the automatic breaker, Q, of the IES is formed. After operating the automatic breaker, the voltage at which the diode transmits is applied to the diode assembly of the protection unit. The magnet system coil current begins to flow through the resistor and diode assembly. The magnet system power is dissipated in the coil and in the protection unit resistance. At this point, the MHD facility operation cycle has ended.

The MHD facility readiness for a shot is determined on the basis of the analyses of the facility parameters and the passage of commands.

5.5 HOT-FIRE TESTS

5.5.1 Operational Check List

The MHD facility is considered to be prepared for operation when:

1) visual inspection of the electrical assembly and wiring has been made with bolted connections tightened if necessary;

2) electrical assembly and wiring prestarting tests have been performed as well as tests of insulation resistance, insulation electrical strength, and excitation circuit resistance, if necessary;

3) the MHD facility preparation for operation in the cold run mode, the cold run, and the analysis of the results have been performed;

4) MHD channels with plasma generators and stops are inspected and installed;

5) squibs have been installed in the plasma generators and contactors, and conductors have been installed into the breakers;

6) cables have been connected to the squibs, to the electric blasting caps, and to the final-control rack of the CMMRS; and

7) a primer voltage has been applied, the CMMRS has been turned on, and there is a message in the CMMRS that the MHD facility is ready for a firing run.

5.5.2 Control Logic

The control logic diagram is shown in Figure 47. Simplified plots of the plasma generator pressure and channel and magnet currents and voltages are shown in Figure 48. These plots reflect a qualitative variation of the parameters and an operation cyclogram for commutators of the Pamir-3U facility.

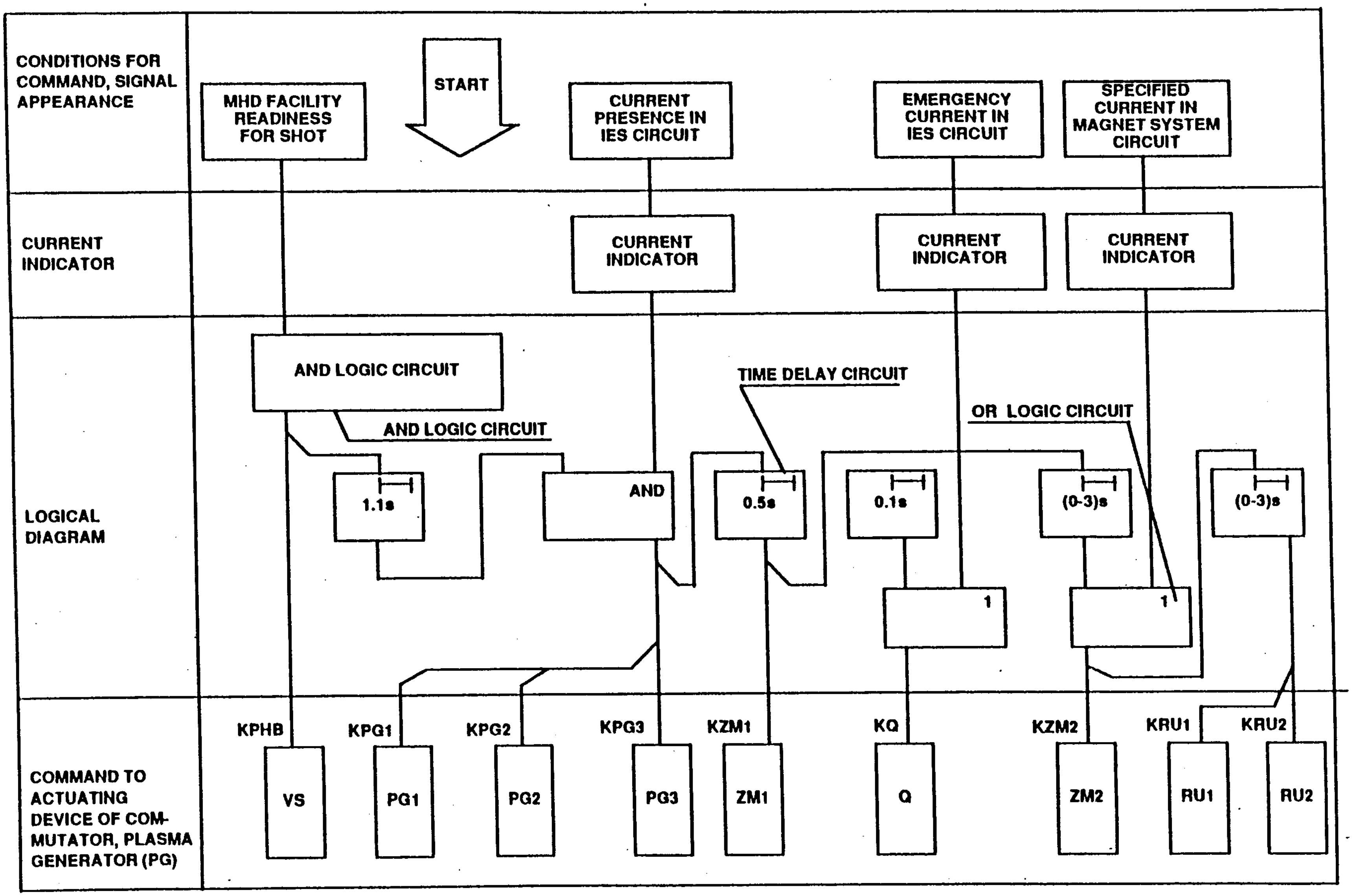


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Figure 47 CMMRS Logic Control Circuit

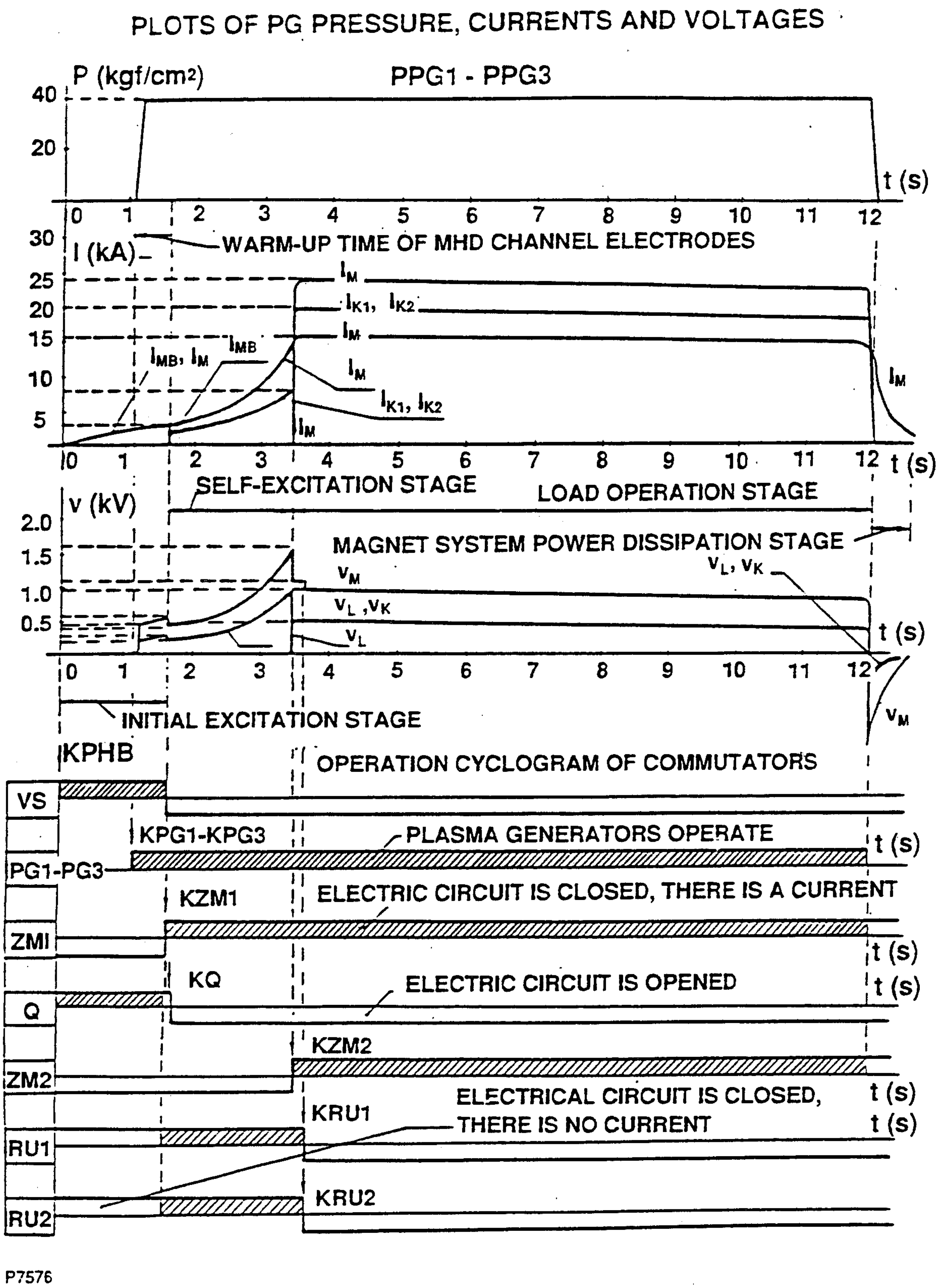


Figure 48 Pressure, Current, and Voltage Histograms of the Pamir-3U MHD Facility Operation

5.5.3 Test Operation

By pressing the "START" button at the control desk, or according to the preset time, or in response to an outside signal, a KPHB command is sent to turn on the VS thyristor switches of the IES. This operation powers the magnet system coil according to the circuit: "+" IES, L, "-" IES, which is shown in Figure 39. Subsequently, the MHD facility operates in the automatic control mode.

The initial excitation current of 2.8 ± 0.2 kA in the circuit being considered is set within 1.6 s. Within 1.1 s after the KPHB command is sent, and with the presence of the correct circuit current, the KPG1, KPG2, and KPG3 commands are sent to start the plasma generators. The MHD facility operates in the no-load condition for 0.5 s, and in so doing, the MHD channel electrodes are heated, and initial excitation circuit current increases to a set value. A KZM1 command is then sent to the ZM1 contactor. At the instant of connection of the MHD channels to the magnet system, their voltage is more than the IES voltage. Thus, a disabling voltage is applied to the VS thyristor switches, and the current in the IES circuit is discontinued.

After the initial excitation current interruption, the MHD facility operates in the self-excitation mode, the current increases, flowing along the circuit: "+" K3, RU2, RU1, ZM1, L, K1, K2, "-" K3. Within 0.1 s after the KZM1 command is sent, a KQ command is sent to the automatic breaker Q which turns the IES off, in the de-energized condition.

When the rated current of 14 ± 2 kA in the excitation circuit is reached, in response to a signal from a current transducer, or with a time delay from the KZM1 command being sent (for duplication purposes), a KZM2 command is sent to the ZM2 contactor, and in this case, the load is connected. Simultaneously, or with a time delay from the KZM2 command, the KRU1 and KRU2 commands are sent to the RU1 and RU2 breakers, which are then opened, causing the ballast resistance R_b to be brought into the excitation circuit, in order to limit the current to a preset level. The MHD facility is then transferred to the mode of operation of power delivery to the load. The load can also be connected to the MHD facility at the beginning of self-excitation stage.

The CMMRS design allows for a reduction of the MHD facility operation time at the load. In that case, the KPG1, KPG2, KPG3 commands are sent to start the plasma generators from the "START" button on the control desk, or according to a preset time in the CMMRS, or from an outside signal. After a preset time, the KPHB command is sent. Within 1.6 s after the KPHB command is sent, the KZM1 command is sent to the ZM1 contactor. The MHD facility then operates in a manner similar to that stated above.

For the purpose of obtaining more information from the preliminary acceptance tests in Russia about the MHD facility operation at the loads of 15, 20 and 25 mΩ during one firing run, two contactors were added to the load composition. The commands to these contactors were provided by the CMMRS. Before the firing run, the load initial resistance of 25 mΩ was set. After contactor operation, a part of the load resistance was shunted in turn, and the resistance was sequentially reduced to the values of 20 and 15 mΩ.

At the instant of termination of the operation of the plasma generators, a rapid rise of the MHD channel inner resistance occurs, and the voltage at which the diode transmits is applied to the diode assembly of the protection unit. The magnet system coil current begins to flow through the resistor and diode assembly of the protection unit. The magnet system power is dissipated in the resistance of electrical magnets and in the resistance of the protection unit. At this point, the MHD facility operating cycle is finished.

The ballast resistance design allows for a resistance variation through an outer commutation. The time delay duration for control command formations can also be adjusted. Depending on the proposed operation mode and expected parameters, the indicated adjustments are performed during the MHD facility preparation for firing runs.

5.6 PREDICTED PARAMETERS OF THE PAMIR-3U MHD POWER SYSTEM

The MHD flow calculation is performed using a quasi-one-dimensional method, which allows the working media thermodynamic properties to vary including the calculation of chemical reactions. The calculated combustor pressure/temperature dependencies for the GP-77 Plasma Generator are given in Figure 49. Because the pressure/temperature dependence in the low temperature end of the range of GP-77 operation is nearly linear, the calculated analysis of Pamir-3U MHD power system was performed in a constant combustor pressure mode for the following combustor pressure levels: P_c = 52 and 40-45 kg_f/cm^2 (with a throat area A = 73.46 cm^2), and P_c = 30 kg_f/cm^2 (with A = 80 cm^2).

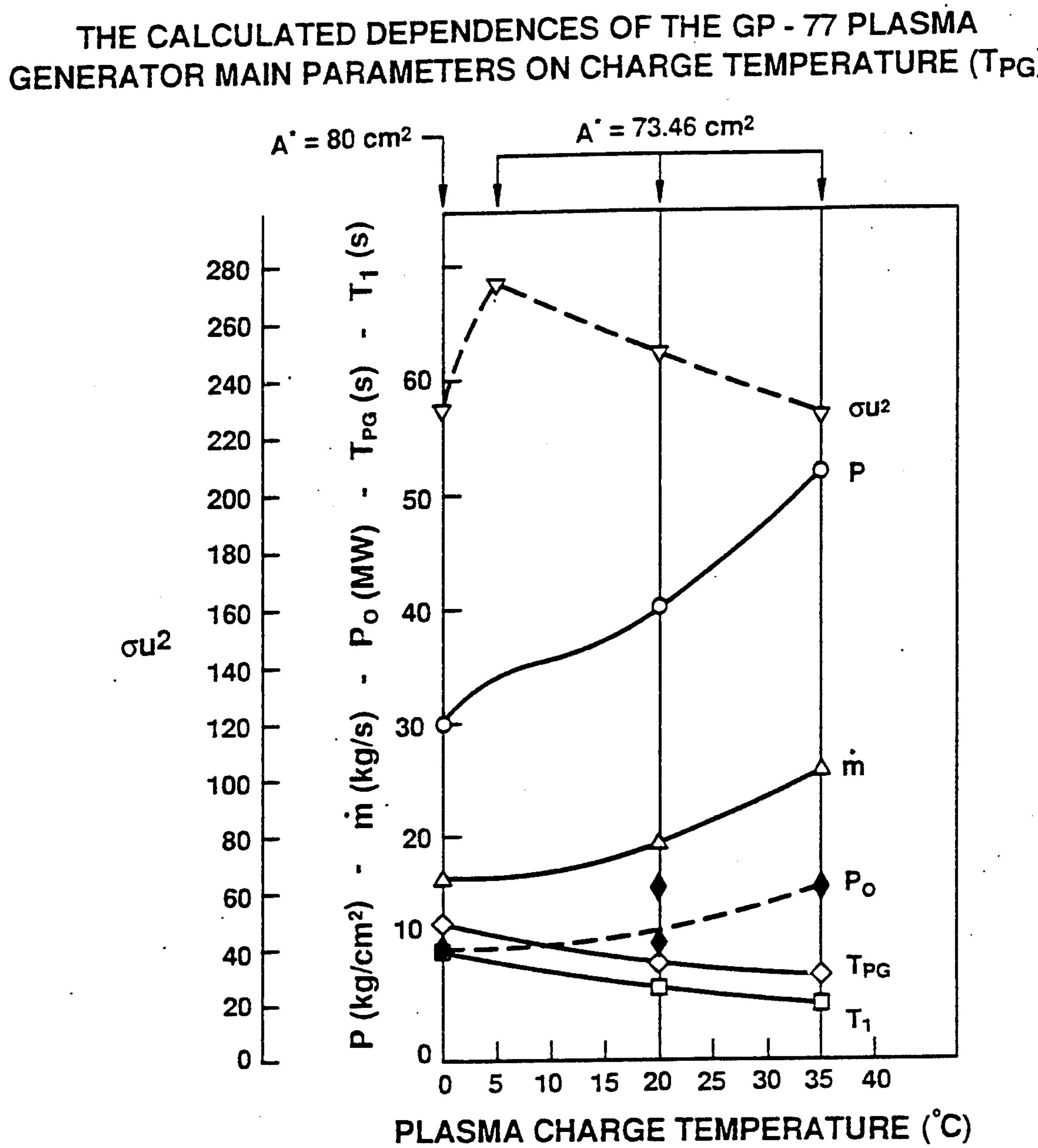
The pressure level of P_c = 52 kg_f/cm^2 was considered to be maximum, the pressure level of P_c = 40-45 kg_f/cm^2 was considered to be nominal, and the pressure level of Pc = 30 kg_f/cm^2 was considered for the mode of maximum current pulse duration at the load.

The geometrical dimensions of the flow side of the MHD channel IM112-5 for the accelerating and the electrode zones are given in Table 17. The electromagnet parameters of the MHD generator magnet system are also given in Table 17 for the conventional coil connection.

The external circuit resistance (bus bar, current conduction elements, etc.) was taken into account by adding additional ohmic resistance (3 mΩ) to the electromagnet winding resistance. The initial temperature of the electromagnet winding was assumed to be 40°C and the initial electromagnet winding resistance was assumed to be 61 mΩ.

The process of the initial magnet excitation of the Pamir-3U facility from the storage batteries was not modeled. Thus, no predictions of its performance are available to compare with the test results. The self-excitation process was considered to start at the time that the self-excitation current reached 2.5 kA. The main calculated output parameters of the Pamir-3U MHD power system for operation at the predetermined ohmic load R = 20 ± 5 mΩ are given in Table 18. The comparison of the technical requirements and the calculated estimates led to the conclusion that the Pamir-3U MHD Power System meets all technical requirements within the range of normal operating modes of the system.

Since the Pamir-3U MHD Power System according to the technical requirements shall operate in the three different power modes, which are shown as modes 1 to 3 in Table 18, the calculated currents and voltages in the MHD facility circuit for each mode are given in the table. During the actual experiment, information from the corresponding analytical run was used in order to define or refine the expected output parameters or to protect the facility power parts from overload or breakage.



P - PRESSURE INSIDE THE COMBUSTION CHAMBER (kg/cm²)

ṁ - PLASMA MASS FLOW RATE (kg/s)

σu^2 - PLASMA POWER COMPLEX (mho/m) (km/s)²

T_{PG} - TOTAL BURNING TIME (s)

T_1 - EXPECTED PAMIR - 3U LOAD PULSE DURATION (s) (CONVENTIONAL OPERATION MODE)

P_0 - REQUIRED OUTPUT POWER (MW_e)

P2970

Figure 49 Calculated Performance of the GP77 Plasma Generators as a Function of Initial Charge Temperature

TABLE 17
CALCULATED PARAMETERS OF THE POWER UNIT OF THE PAMIR-3U MHD POWER SYSTEM

Parameter				Value
1.	**MHD channel (unit IM1112-5.00.000)**			
1.1	Channel cross-section dimensions:			
	- acceleration zone inlet (F = 1.05 A)			68 x 112 mm^2
	- electrode section inlet			159 x 158 mm^2
	- electrode section outlet			257 x 159 mm^2
1.2	Electrode section length			1008 mm
1.3	Number of channels IM112-5 (K1, K2, K3)			3
2.	**Magnet system (Unit IM1-3.01.10.000)**			
2.1	Number of coils			4
2.2	Number of sections			6
2.3	Rated connection of sections			in series
2.4	Total inductance (with mutual induction)			52.4 mH
2.5	Total ohmic resistance of coil (at 20°C)			56 mΩ
2.6	Distance between adjacent coils (for copper)			275 mm
2.7	Induction parameter in the center of working volume			
	- for central space (K3)			0.247 T/kA
	- for side spaces (K1, K2)			0.204 T/kA
2.8	External circuit resistance, not more than			3 mΩ
2.9	Coil mass (copper)			4500 kg
3.	**Plasma generator (unit GP-77.00-0000)**			
3.1	Plasma mass flow rate			18.5-26 kg/s
	Combustor pressure			38-53 kg_f/cm^2
3.2	Power complex at channel inlet:			
	- Charge temperature	35	20	0 °C
	- Plasma generator pressure	52	40	30 kg_f/cm^2
	- Plasma generator throat area	73.5	73.5	80 cm^2
	- Experimental power complex ($\sigma^* u^2$)	230	250	230 (mho/m)(km/s)

σ = integral electrical conductivity
u = flow velocity

4.	**IES current (unit IM1-3.04.00.000)**	2.5 - 3 kA

TABLE 18
MAIN OUTPUT PARAMETERS OF THE PAMIR-3U MHD POWER SYSTEM
FOR OPERATION AT LOAD RESISTANCES OF 20 ± 5 MΩ

	Parameter Name		Operation Mode 1	2	3
1.	Electric power in the load				
	- technical requirement	MW	15	10-15	10
	- calculation	MW	15	11-13.5	10
2.	Current pulse duration in load				
	- technical requirement	s	-	6-6.5	8.5-9.5
	- calculation	s	4.5 - 5	6-6.5	10
3.	Current amplitude in the load	kA	27.5-32	21-30	17-24
4.	Load voltage	V	480-550	410-530	325-470
5.	Time of achievement of rated power from plasma generator start not more than	s	2	2	2
6.	Magnet system current	kA	15.5-16	14-15.6	10-13
7.	K3 channel (central) current	kA	15.5-16	14-15.5	10-13
8.	Current of K1 and K2 channels	kA	21-24	20-22	15-18
9.	K3 channel voltage	V	850	720-800	660
10.	K1 and K2 channel voltage	V	480-550	410-530	325-470
11.	Ballast resistance	mΩ	15-25	10-20	20
12.	Initial excitation current not less than	kA	2.5	2.5	2.5
13.	PG pressure (rated)	kg_f/cm^2	52	40-45	30
14.	Total operation duration	s	7.4	8.5-9	12
15.	Charge temperature	°C	35	20-25	0
16.	Throat area	cm^2	73.46	73.46	80
17.	Plasma mass flow rate	kg/s	26	20-22	16
18.	Plasma power complex at channel inlet (σu^2)	$(mho/m)(km/s)^2$	230	250	230

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6.0 PRELIMINARY ACCEPTANCE TEST PROGRAM IN RUSSIA

6.1 THE TEST SITE DESCRIPTION

The preliminary acceptance test program was conducted at the Geodesiya Research Institute, Krasnoarmejsk, Russia. This location is approximately 50 km northeast of Moscow. The Geodesiya test-site No. 75 occupies 1.2 hectares (3 acres) and is used for testing pulsed MHD facilities. The test site involves two test stands, a laboratory building used for measurements and analysis, and an initial excitation system building. The two stands are the OP-8 hot-fire installation where the acceptance tests for the Pamir-3U facility were performed, and the OP-1 hot-fire installation where the MHD channels and plasma generator cases were restored. The test site periphery is fenced. Figure 50 shows an overview of the OP-8 test stand and associated buildings.

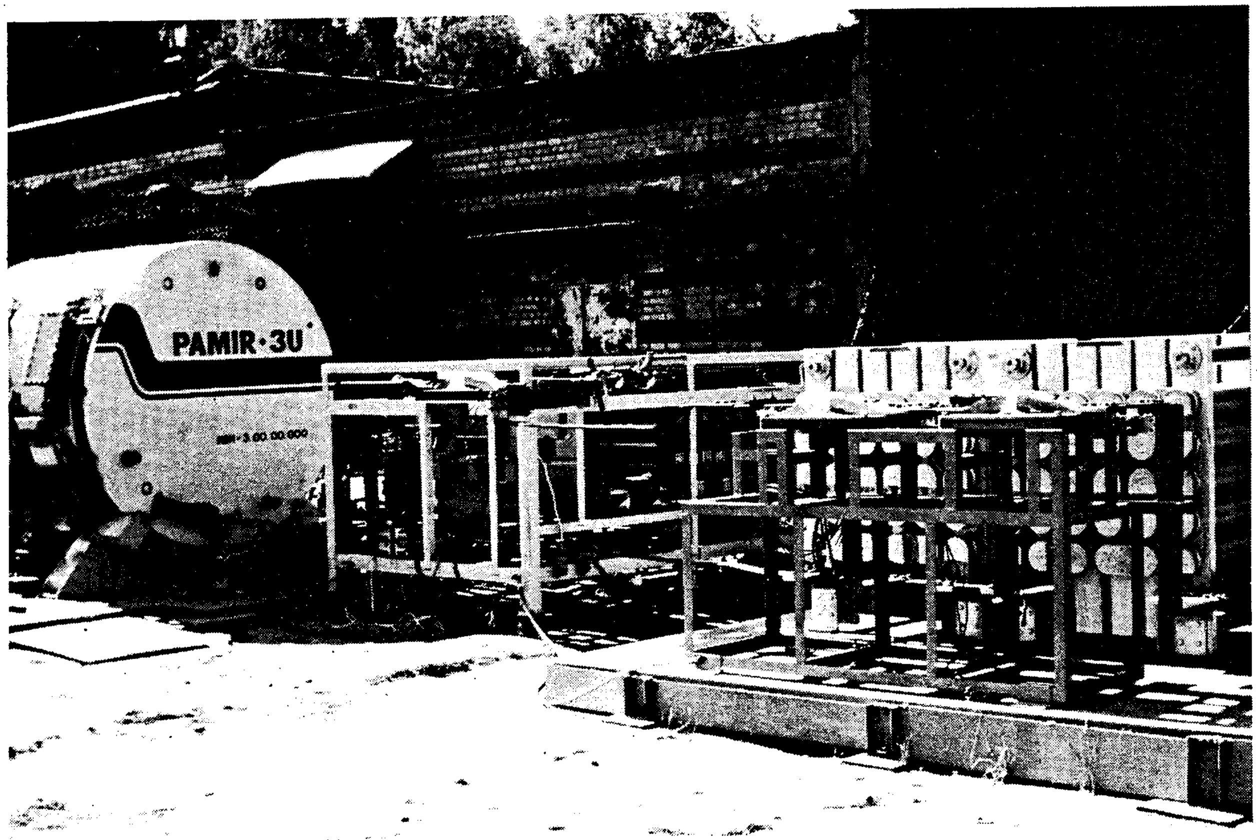
The OP-1 installation is a brick building with a steel reinforced concrete floor. It consists of a storage building of 50 m^2 for the test facility location and of two buildings of 36 m^2 each for location of measuring and commutation equipment. To provide the cable communications, the stand is equipped with cable channels. The stand is equipped with a hoist rated for a 5 ton load. The building is supplied with 380/220 V ac and 27 V dc power.

The OP-8 is a steel-reinforced concrete test stand measuring 75 m^2 with a steel-reinforced concrete pad support that is used as a foundation for the installation of the MHD generator. In front of the stand, a ferroconcrete site is available with metal anchors for fixing the MHD facility. At the stand transit, a gas exhaust zone, 400 m in length and 6 m in width, is available.

Two brick buildings are joined to the stand: the right one measures 1200 m^2, and the left one measures 480 m^2. The height of the buildings is 4.4 m. The buildings are used for installation of the test equipment and devices. In order to provide safety cable communication, the stand and the buildings are equipped with cable channels. The OP-8 is supplied by 380/220 V ac and 27 V dc power.

The two stands, OP-1 and OP-8, are connected by cable to the measurements and analysis laboratory building. The measuring laboratory is a brick building with 80 m^2 floor space and 2.8 m in height. Any measuring equipment and the control console are located here. Control and supervision of the installation operation are remotely performed from the measuring laboratory.

The plasma generator case assembly was performed at Geodesiya test site No. 4, inside the No. 108 installation, which is an assembly shop equipped with special tools, rigs, and hoists. Also, a thermal chamber is located at test site No. 4 for climatic testing up to a maximum temperature of + 60°C. The thermal chamber was used for the pre-test thermal conditioning of the plasma charges. The distance between the test site No. 75 and the test site No. 4 is about 3 km.



P7610

Figure 50 Geodesiya MHD Facility Test Site

6.2 TEST DESCRIPTION AND OBJECTIVES

The test objectives were as follows:

- confirm by hot-firing tests the serviceability of the OE-72 and OE-304 charges that had expired service lives for the acceptance tests of the Pamir-3U MHD facility;

- to adjust and check the Pamir-3U MHD Facility operation in the real operation mode;

- to demonstrate the agreement of the Pamir-3U MHD Facility output parameters with those specified by the technical requirements, which are listed below:

Parameter	Value
Maximum output power	15 MW_e*
Nominal output power	10 - 15 MW_e
Maximum pulse duration	9 ± 0.5 s**
Nominal pulse duration	6 - 6.5 s
Electrical load resistance	20 ± 5 mΩ

* a nominal load resistance value within the range of 15 to 25 mΩ

** a total output power not less than 10 MW_e, using BP-10 propellant at a temperature of +5°C and GP-77 plasma generators

6.3 TEST HARDWARE

6.3.1 The main components of the Pamir-3U MHD facility are listed in Table 19.

TABLE 19
PRINCIPAL COMPONENTS OF THE PAMIR-3U FACILITY

No.	Component	Designation	Quantity
1.	Power Unit (PU)	IM1-3.01.00.000	1
2.	Electrical Equipment Unit (EEU)	IM1-3.02.00.000	1
3.	Initial Excitation System (IES)	IM1-3.03.00.000	1
4.	Control, Measuring, Monitoring and Recording System (CMMRS)	RAN 36.00.000	1
5.	Reserve CMMRS	CMMRS-U	1
6.	Dummy Load	KM-1203.00.000	1

The tests numbered 1, 2, and 3 were performed using the GP-86 plasma generators, which have an operating time of about 5 s. The reserve CMMRS, designated as CMMRS-U, was used for these firing runs. The CMMRS-U consists of the following main units: one main control board (MCB); one ignition unit (IU); one module of measuring amplifiers; recording equipment; and power and measuring cables. The power supply is 220 V AC.

The MCB generates commands for the executive devices according to a logic diagram and the technical assignment for the firing run, accounting for the limited values of the IES current and the magnet current. The IU consists of eight identical ignition modules and generates the necessary impulses for the ignition devices. The unit of measuring amplifiers consists of five amplifiers for

current pulses and a summer for the input, two signal amplifiers with a voltage divider, and three amplifiers of signals from pressure transducers. At the Geodesiya Research Center a mirror-galvanometer oscillograph and a Hewlett-Packard digital recorder were used as recording equipment.

The tests numbered 4 and 5 were performed using standard GP-77 plasma generators and the standard CMMRS. The plasma generators and propellant charges used for the Pamir-3U MHD facility acceptance tests in Russia are listed in Table 20.

TABLE 20
EQUIPMENT USED FOR THE PRELIMINARY ACCEPTANCE TESTS

Test No.	Channel No.	Plasma Generator Type	Plasma Generator Case No.	Propellant Type	Propellant Batch	Charge No.	Post Test Condition
1	1	GP-86	03-02	OE-304	32-89-L	4	Hardware was in normal condition. PG cases need repair. MHD channels are suitable for reuse without refurbishment.
	2	GP-86	01-09	OE-304	32-87-L	10	
	3	GP-86	01-08	OE-304	32-87-L	12	
2	1	GP-86	03-04	OE-304	69-88-L	7	PG cases and MHD channels need refurbishment.
	2	GP-86	03-09	OE-304	69-88-L	6	
	3	GP-86	02-11	OE-304	69-88-L	11	
3	4	GP-86	03-07	OE-304	32-89-L	12	Hardware normal condition. PG cases need repair. MHD channels are suitable for reuse without refurbishment.
	7	GP-86	02-14	OE-304	32-89-L	14	
	8	GP-86	03-03	OE-304	32-89-L	22	
4	4	GP-77	25-05	OE-72	11-93-L	6	PG cases and MHD channels need refurbishment.
	7	GP-77	25-09	OE-72	11-93-L	4	
	8	GP-77	25-13	OE-72	11-93-L	5	
5	5	GP-77	25-10	OE-72	48-89-L	20	PG cases and MHD channels need refurbishment.
	6	GP-77	25-12	OE-72	48-89-L	17	
	9	GP-77	27-05	OE-72	48-89-L	23	

6.3.2 Hardware Condition After the Firing Runs

During the preliminary acceptance tests that were performed, all components and subsystems operated in the rated mode, but because of a delay in the development of the standard CMMRS, this unit operated as a part of the Pamir-3U MHD facility for only Test Nos. 4 and 5. A short description of the condition of all of the components of the Pamir-3U MHD facility after firing runs is given in Table 20.

6.3.2.1 The Power Unit

The plasma generators operated in the rated mode. Their condition after the firing runs was good. There are no indications of damage or repairs required.

The MHD channels operated in the rated mode. On the inner surfaces, there was minor uniform erosion of the wall material. During the runs using GP-86 plasma generators, refurbishment of the gas dynamic duct was performed after two firings. Load-bearing shells and flange joints were in a good condition. There were no other indications of damage or repairs required.

Because of improper gluing, some peeling of the fabric cloth-based laminate spacers in the magnet system occurred. The metal protective shields were warped, and the paint work on the buses close to exhaust flow was burned. On the base plate surface, a narrow zone of electrical contact was detected, which may be explained by an electrical contact between the plasma flow and the metal base plate.

6.3.2.2 Initial Excitation System and Electrical Equipment Unit

There were no problems with the operation of the IES and the electrical equipment.

6.3.2.3 Control, Measuring, Monitoring, and Recording System

In the Test No. 4, the load voltage was not recorded. In the other hot-fire tests, there were no other indications of damage or repairs required for the operation of the reserve or the standard CMMRS's except for the measuring cable that was broken.

6.4 TEST PROGRAM

The test program for the Pamir-3U MHD Facility acceptance tests in Russia is presented in Table 21.

In order to measure the MHD facility parameters over the entire specified load resistance range, the dummy resistance was configured for commutation for resistances of 25, 20 and 15 mΩ during Tests No. 1, 2, and 3.

The test sets and their initial parameters are presented in Table 22.

TABLE 21
PRELIMINARY ACCEPTANCE TEST PROGRAM

Test No.	Test Goal	Plasma Generator Type	Notes
1.	Acceptance tests of charges with expired service life		
1.1	Acceptance test of OE-72 charge	GP-77	
1.2	Acceptance test of OE-304 charge	GP-86	
2	Acceptance tests of the Pamir-3U MHD facilities		
2.1	Check-out of the Pamir-3U MHD Facility system operation	GP-86	With the dummy load commutation during the run
2.2	Check-out of the Pamir-3U MHD Facility system operation	GP-86	With the dummy load commutation during the run
2.3	The Pamir-3U MHD Facility test in the precalculated operation mode (demonstration of the nominal power mode)	GP-86	With the dummy load commutation during the run
2.4	Demonstration of the maximum pulse duration mode using the slowly burning charge lot	GP-77	
2.5	Demonstration of the maximum power mode	GP-77	

TABLE 22
PRELIMINARY ACCEPTANCE TEST SETS

Test No.	Propellant Type	Charge Batch	Charge Temp. (°C)	Ballast Resist. (mΩ)	Excitation Duration (s)	Load (mΩ)
1.	Acceptance tests of charges with expired service life					
1.1	BP-10F	41-86L	20	N/A	N/A	N/A
1.2	SPK-14S	38-87L	20	N/A	N/A	N/A
2.	Acceptance tests of the Pamir-3U MHD facility					
2.1	BP-10F SPK-14C	32-89L 32-87L	20	20	2.6	25, 20, 15
2.2	SPK-14C	69-88L	20	10 (connected at the beginning of the run)	2	25, 20, 15
2.3	BP-10F	32-89L	20	20	1.2	25, 20, 15
2.4	SPK-10M	11-90L	20	20	1.4	20
2.5	BP-10F	48-89L	35	24	1.4	16

6.5 TEST RESULTS

6.5.1 Tests of Propellant Charges with Expired Service Lives

6.5.1.1 The Test Goal

The test goal was to establish the working ability of OI-72 and OI-304 charges after a prolonged storage time, which exceeded the expiration of the guarantee period. Thus, preliminary authorization from Soyuz to extend the operation period until 1 April 1995 was required.

6.5.1.2 Test Hardware

The hardware tested included GP-77 and GP-86 Plasma Generators. The GP-77 generators used BP-10F Propellant, and the GP-86 generators used SPK-14C propellant. The GP-77 test was conducted on 21 July 1994 and the GP-86 test on 22 July 1994. The hardware characteristics are described below.

GP-77 Plasma Generator Test Set

Case:	GP-77 No. 25-11
Charge:	OI-72/41-86L No. 25 (BP-10F propellant)
Igniter:	DI-91/28-88L

GP-86 Plasma Generator Test Set

Case:	GP-86 No. 02-12
Charge:	OI-304/38-87L No. 15 (SPK-14C propellant)
Igniter:	DI-91/28-88L

6.5.1.3 Test Conditions

The firing tests of the GP-77 and GP-86 plasma generators were performed at a special test stand at the Geodesiya Research Center. At the time that the tests were conducted, the charge temperature was equal to +20°C.

6.5.1.4 Predicted and Actual Test Parameters

For the GP-77 plasma generator, the mean gage pressure inside the combustion chamber was predicted to be 43 atm, and the combustion duration was forecast to be 8.73 s. For the GP-86 plasma generator, the initial gage pressure inside the combustion chamber was predicted to be 26 atm, and the final gage pressure forecast to be 36.5 atm. The combustion duration was expected to be 6 s.

For the GP-77 plasma generator, the mean gage pressure inside the combustion chamber was 41 atm, and the charge combustion duration was 8.7 s. For the GP-86 plasma generator, the initial gage pressure inside the combustion chamber was 28 atm, and the final gage pressure was 39 atm. The charge combustion duration was 5.6 s.

6.5.1.5 The Results of Plasma Generator Case Restoration After the Hot Fire Tests

The case status was satisfactory. No burn-out was observed. After restoration, the cases were satisfactory for further use.

6.5.1.6 Conclusions

During the hot-fire tests, the operational capability of the OI-72 and OI-304 plasma charges was confirmed for storage durations that exceeded the expiration date by five and six years, respectively. These times were the greatest time extensions for the charges delivered from Bishkek. The pressures measured inside the combustion chamber and the combustion durations were in satisfactory agreement with those calculated. The OI-72 and OI-304 charge batches that were proposed for use for the adjusting and acceptance tests of the Pamir-3U MHD facility were approved.

According to the results obtained from the tests that were performed, the expiration date of the OI-72 and OI-304 charges delivered from Bishkek was extended up to 1 April 1995. This extension was recorded in the Soyuz authorization dated 28 August 1994.

6.5.2 The Pamir-3U MHD Facility Preliminary Acceptance Tests

6.5.2.1 Results of the Cold Run Tests of the Pamir-3U MHD Facility in Russia

After installing the Pamir-3U MHD facility at the test site according to the Section 4.3 of the Operation Manual IM1-3.00.00.000 OM[1], the Cold runs were conducted.

6.5.2.2 Results of the Test for Insulation Resistance and Insulation Electrical Strength

The results of the test for insulation resistance and insulation electrical strength between circuits with different potentials are given in Table 23.

TABLE 23
INSULATION STRENGTH TEST RESULTS

	Testing Parameter		Value: Specified	Value: Actual
1.	Insulation electrical strength between Electrical Equipment Unit (EEU) bus terminals			
	3 and 5	kV, dc	5	5
	3 and 6	kV, dc	5	5
	5 and 6	kV, dc	5	5
2.	Insulation resistance between Electrical Equipment Unit (EEU) bus terminals,		Not less than	
	3 and 5	MΩ	20	500
	3 and 6	MΩ	20	70
	5 and 6	MΩ	20	500

6.5.2.3 Test Results for the Insulation Resistance and Insulation Electrical Strength Between Current Leading Circuits and the Grounding Devices

The results of the tests for insulation resistance and insulation electrical strength between current leading circuits and the grounding device are given in Table 24.

TABLE 24
GROUND LOOP INSULATION RESISTANCE TEST RESULTS

	Testing Parameter		Value (Name and Units) Specified	Actual	Remarks
1.	Insulation electrical strength	kV, dc	5	5	
	Insulation resistance	MΩ	10	160	with the CMMRS cables disconnected
		MΩ	10	150	with control and measuring cables connected

6.5.2.4 Excitation Circuit Resistance Test Results

The results of the excitation circuit resistance tests are given in Table 25.

TABLE 25
EXCITATION CIRCUIT RESISTANCE TEST RESULTS

Testing Parameter	Value Specified	Actual	Remarks
Circuit resistance in MΩ between the Power Unit (PU) terminals,			
"+" K3 and "-" K1	57.5 ± 1.5	57	before firing runs
"+" K3 and "-" K2	57.5 ± 1.5	56.9	
"+" K3 and "-" K1	*	64	40 minutes after firing run # 5
"+" K3 and "-" K2	*	63.8	
"+" K3 and "-" K1		60.9	46 hours after firing run # 5
"+" K3 and "-" K2	*	60.8	
"+" K3 and "-" K1		56.8	8 days after firing run # 5
"+" K3 and "-" K2	*	56.7	

Note: * - not specified.

6.5.2.5 Test Results for Cold Run Mode Facility Operation

The results of the tests of the facility operation in cold run mode are listed below.

1) Initial excitation current is 2.7+0.1 kA . The specified value is 2.8 $\pm$ 0.2 kA.

2) Time for the achievement of 95 % of the initial excitation current is 1.6 s. The specified value is 1.6 s.

3) The PG1-PG3 generators start time is 1.1 s after the KPHB command. The specified value is 1.1 s.

4) Contactor ZM1 switching on time is 1.6 s after the KPHB command. The specified value is 1.6 s.

5) Time of the automatic protection device disconnection from the Initial Excitation System (IES) is 1.7 s after the KPHB command. The specified value is 1.7 s.

6) The TM, TK1, TK2, TN currents registered as present.

7) The KPHB, KPG1-KPG3, KZM1, KQ, K3M2-K3M4, KPY1, KPY2 commands registration according to the specified cyclogram.

6.5.2.6 Test Results of Contactor and Breaker Operation

Contactor and breaker operation test results:

1) The mechanical closing of the current conductors of the ZM1, ZM2, ZM3, and ZM4 contactors and the mechanical breakage of the current conductors of a breaker (one from the batch) were tested using pyrotechnical equipment.

2) The closing of the current conductors of the contactors and breakage of the current conductors of the breaker were performed according to the requirements of the technical documentation.

6.5.2.7 Conclusions of the Cold Run Tests of the Pamir-3U

The Pamir 3-U MHD facility is ready for the firing runs.

6.5.2.8 Test Results

The preliminary acceptance tests were conducted from 27 July 1994 to 10 August 1994. The test program consisted of five tests that were performed at the Geodesiya Research Institute, Krasnoarmejsk, Russia. Figure 51 shows a photograph of the Pamir-3U MHD during hot-fire testing.

The Pamir-3U MHD facility operating results from the tests are shown in Tables 26 to 30. Listed in the tables are the values corresponding to the maximum power output reached within the experiments. The maximum power values were calculated by two different procedures.

$$P_L = (V_L)^2/R_L$$
$$P_L = (V_L)\,(I_L)$$

Both values are given in the Tables. The first method uses only one measured parameter. Thus, the experimental error effect is less, resulting in a smaller measurement error. However, the first method relies on a constant load resistance, which may not be the case. In Test Nos. 1 and 2, the load current was not measured. Thus, in the Tables 27 and 28, there is only one power value, which is defined by the voltage. The measurement diagram of the electric parameters reported is shown in Figure 52.

The time dependence of the main parameters are shown on Figures 53 to 57. The load voltage (V_L) shown on these figures was measured on the channel side of the contactors ZM2, and its time dependence corresponds to the channels K1 and K2 voltage time dependence.

The acceptance tests in Russia were conducted using the re-certified plasma charges. The age of these charges could reduce their energy. This fact provided some difficulty in defining the preliminary estimate of the expected output performances of the Pamir 3-U MHD facility and also the initial test data specification. Particular difficulty was encountered in the specification of the time of the load and the ballast resistance connection to the circuit as well as determination of the ballast resistance value.

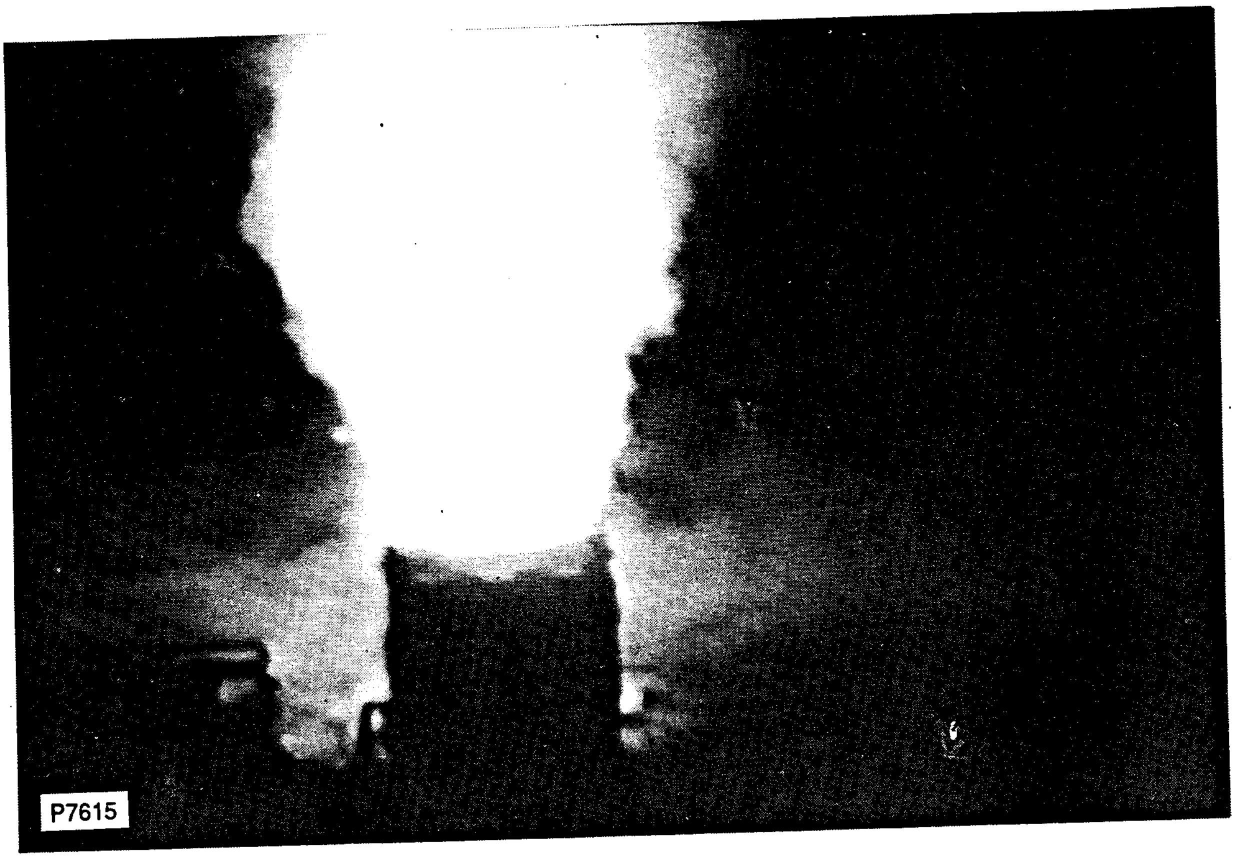


Figure 51 Pamir-3U MHD Power System Hot-Fire Test

TABLE 26
PAMIR-3U MHD FACILITY PARAMETERS OBTAINED DURING TEST NO. 1, 27 JULY 1994

Parameter	Value	Calculated/Measured
Load resistance, R_L	15 mΩ	M**
Load voltage, V_L	406 V	M
Ballast resistance voltage, V_B	315 V	C*
Magnet voltage, V_M	991 V	M
K3 channel voltage, V_{K3}	900 V	C
K2 channel voltage, V_{K2}	406 V	C
K1 channel voltage, V_{K1}	406 V	C
Load current, I_L	27 kA	C**
K1 channel current, I_{K1}	19 kA	M
K2 channel current, I_{K2}	17.5 kA	M
Magnet current, I_M	15.75 kA	M
Initial excitation current, I_{IES}	2.5 kA	M
Load power, $P_L = V_L^2/R_L$	11 MW_e	C**
Excitation time, t_E	2.57 s	M
Pulse duration in the load, t_L	2.35 s	M

Initial data.

The propellant type: SPK-14C for PG1, PG2; BP-10F for PG3.
The charge type: OI-304. The charge temperature: 20°C.
The ballast resistance value: 20 mΩ.

* Without accounting for the ballast resistance increase caused by heating.

** Without accounting for the load resistance increase caused by heating.

TABLE 27
PAMIR-3U MHD FACILITY PARAMETERS OBTAINED DURING TEST NO. 2, 29 JULY 1994

Parameter		Value			Calculated/Measured
Load resistance, R_L	mΩ	25	20	15	M**
Load voltage, V_L	V	520	483	426	M
Ballast resistance voltage, V_B	V	170	165	165	C*
Magnet voltage, V_M	V	1202	1281	1185	C
K3 channel voltage, V_{K3}	V	852	965	924	C
K2 channel voltage, V_{K2}	V	520	483	426	C
K1 channel voltage, V_{K1}	V	520	483	426	C
Load current, I_L	kA	20.0	24.2	28.4	C**
K1 channel current, I_{K1}	kA	17.5	18.0	19.5	M
K2 channel current, I_{K2}	kA	18.0	19.0	20.5	M
Magnet current, I_M	kA	17.0	16.5	16.5	M
Initial excitation current, I_{IES}	kA		2.6		M
PG1 pressure, P_1	atm		28 - 39		M
PG2 pressure, P_2	atm		28 - 39		M
PG3 pressure, P_3	atm		28 - 39		M
Load power, $P_L = V_L^2/R_L$	MW_e	10.8	11.7	12.1	C**
Excitation time, t_E	s		2.18		M
Pulse duration in the load, t_L	s		2.43		M
PG burning duration, t_{PG}	s		5.6		M

Initial data.

The propellant type: SPK-14C. The charge type: OI-304.
The charge temperature: 20°C.
The ballast resistance value: 10 mΩ (connected before the run).

* Without accounting for the ballast resistance increase caused by heating.

** Without accounting for the load resistance increase caused by heating.

TABLE 28
PAMIR-3U MHD FACILITY PARAMETERS OBTAINED DURING TEST NO. 3, 4 AUGUST 1994

Parameter		Value			Calculated/Measured
Load resistance, R_L	mΩ	25	20	15	M**
Load voltage, V_L	V	565	540	475	M
Ballast resistance voltage, V_B	V	296	318	318	C*
Magnet voltage, V_M	V	964	962	932	C
K3 channel voltage, V_{K3}	V	695	740	775	C
K2 channel voltage, V_{K2}	V	565	540	475	M
K1 channel voltage, V_{K1}	V	565	540	475	M
Load current, I_L	kA	21.0	23.4	28.7	M
K1 channel current, I_{K1}	kA	16.4	18.5	19.5	M
K2 channel current, I_{K2}	kA	16.4	18.5	19.5	M
Magnet current, I_M	kA	15.8	16.6	16.6	M
Initial excitation current, I_{IES}	kA	2.46	2.46	2.46	M
PG1 pressure, P_1	atm	36 - 38	...	49 - 50	M
PG2 pressure, P_2	atm	36 - 38	...	49 - 50	M
PG3 pressure, P_3	atm	36 - 38	...	49 - 50	M
Load power, $P_L = V_L^2/R_L$	MW_e	12.8	14.6	15	C**
Load power, $P_L = V_L*I_L$	MW_e	11.9	12.6	13.6	C**
Excitation time, t_E	s	1.18	1.18	1.18	M
Pulse duration in the load, t_L	s	3.15	3.15	3.15	M
PG burning duration, t_{PG}	s	5.07	5.07	5.07	M

Initial data.

The propellant type: BP-10F.
The charge type: OI-304.
The charge temperature: 20°C.
The ballast resistance value: 20 mΩ.

* Without accounting for the ballast resistance increase caused by heating.

** Without accounting for the load resistance increase caused by heating.

TABLE 29
PAMIR-3U MHD FACILITY PARAMETERS OBTAINED DURING TEST NO. 4, 9 AUGUST 1994

Parameter	Value	Calculated/Measured
Load resistance, R_L	20 mΩ	M**
Load voltage, V_L	509 V	M
Ballast resistance voltage, V_B	282 V	C*
Magnet voltage, V_M	998 V	M
K3 channel voltage, V_{K3}	771 V	C
K2 channel voltage, V_{K2}	509 V	M
K1 channel voltage, V_{K1}	509 V	M
Load current, I_L	22.4 kA	M
K1 channel current, I_{K1}	18.4 kA	M
K2 channel current, I_{K2}	18.2 kA	M
Magnet current, I_M	14.1 kA	M
Initial excitation current, I_{IES}	2.7 kA	M
PG1 pressure, P_1	39 atm	M
PG2 pressure, P_2	41 atm	M
PG3 pressure, P_3	40 atm	M
Load power, $P_L = (V_L^2/R_L)/(V_L I_L)$	12.9/11.4 MW_e	C/C
Excitation time, t_E	1.8 s	M
Pulse duration in the load, t_L	7.13 s	M
PG burning duration, t_{PG}	9.01 s	M

Initial data.
The propellant type: SPK-10M.
The charge type: OI-72.
The charge temperature: 20°C.
The ballast resistance value: 20 mΩ.

* Without accounting for the ballast resistance increase caused by heating.

** Without accounting for the load resistance increase caused by heating.

TABLE 30
PAMIR-3U MHD FACILITY PARAMETERS OBTAINED DURING TEST NO. 5, 10 AUGUST 1994

Parameter	Value	Calculated/Measured
Load resistance, R_L	16 mΩ	M**
Load voltage, V_L	492 V	M
Ballast resistance voltage, V_B	336 V	C*
Magnet voltage, V_M	998 V	M
K3 channel voltage, V_{K3}	830 V	C
K2 channel voltage, V_{K2}	504 V	M
K1 channel voltage, V_{K1}	504 V	M
Load current, I_L	28.5 kA	M
K1 channel current, I_{K1}	20.8 kA	M
K2 channel current, I_{K2}	21.4 kA	M
Magnet current, I_M	14 kA	M
Initial excitation current, I_{IES}	2.6 kA	M
PG1 pressure, P_1	46 atm	M
PG2 pressure, P_2	46.8 atm	M
PG3 pressure, P_3	46 atm	M
Load power, $P_L = (V_L^2/R_L)/(V_L I_L)$	15.1/14 MW_e	C/C
Excitation time, t_E,	1.395 s	M
Pulse duration in the load, t_L	6.36 s	M
PG burning duration, t_{PG}	8.3 s	M

Initial data.
The propellant type: BP-10F.
The charge type: OI-72.
The charge temperature: 35°C.
The ballast resistance value: 24 mΩ.

* Without accounting for the ballast resistance increase caused by heating.

** Without accounting for the load resistance increase caused by heating.

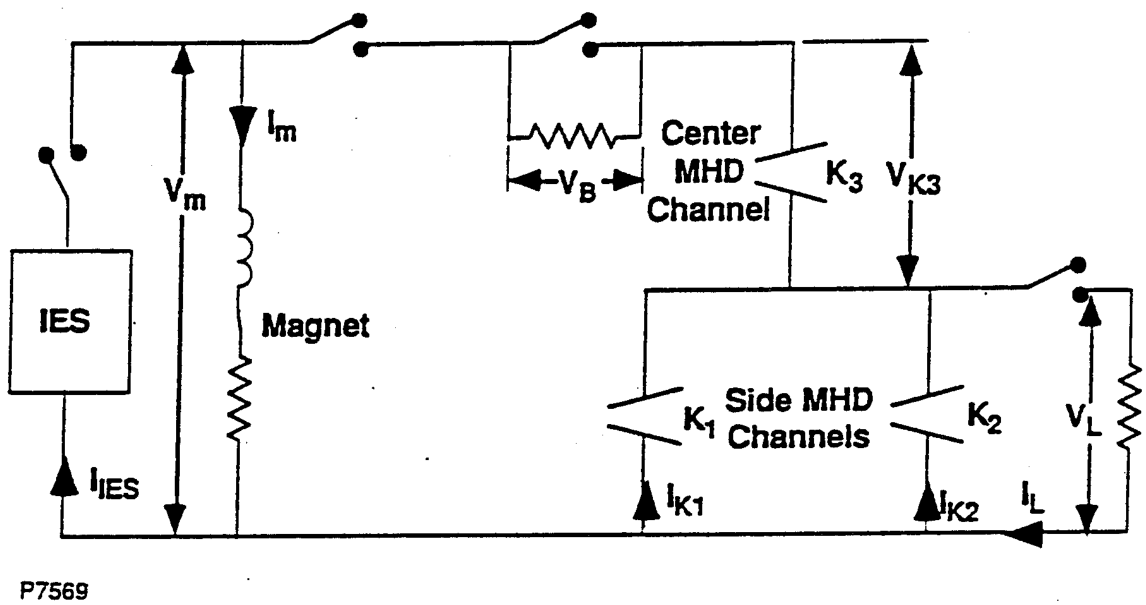


Figure 52 Electrical Measurement Schematic for the Pamir-3U System

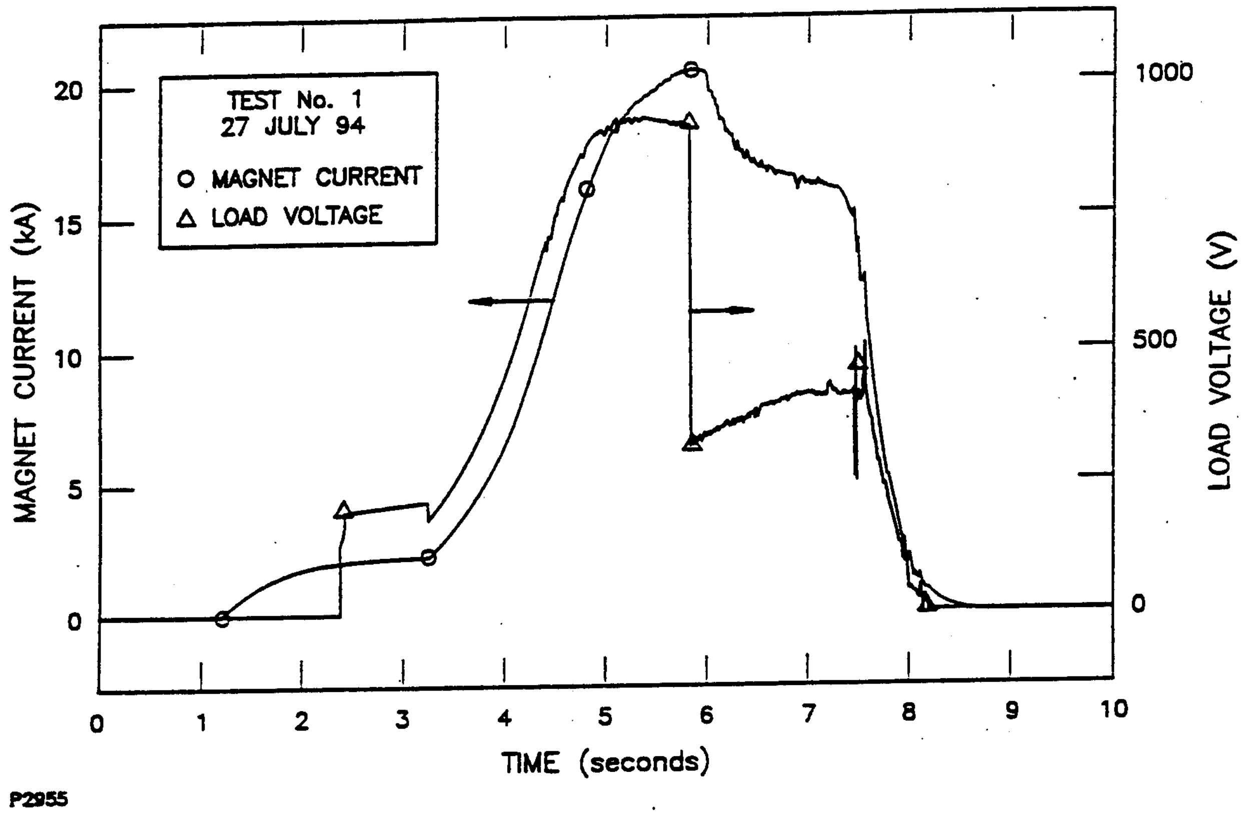


Figure 53 Performance Results from Preliminary Acceptance Test No. 1

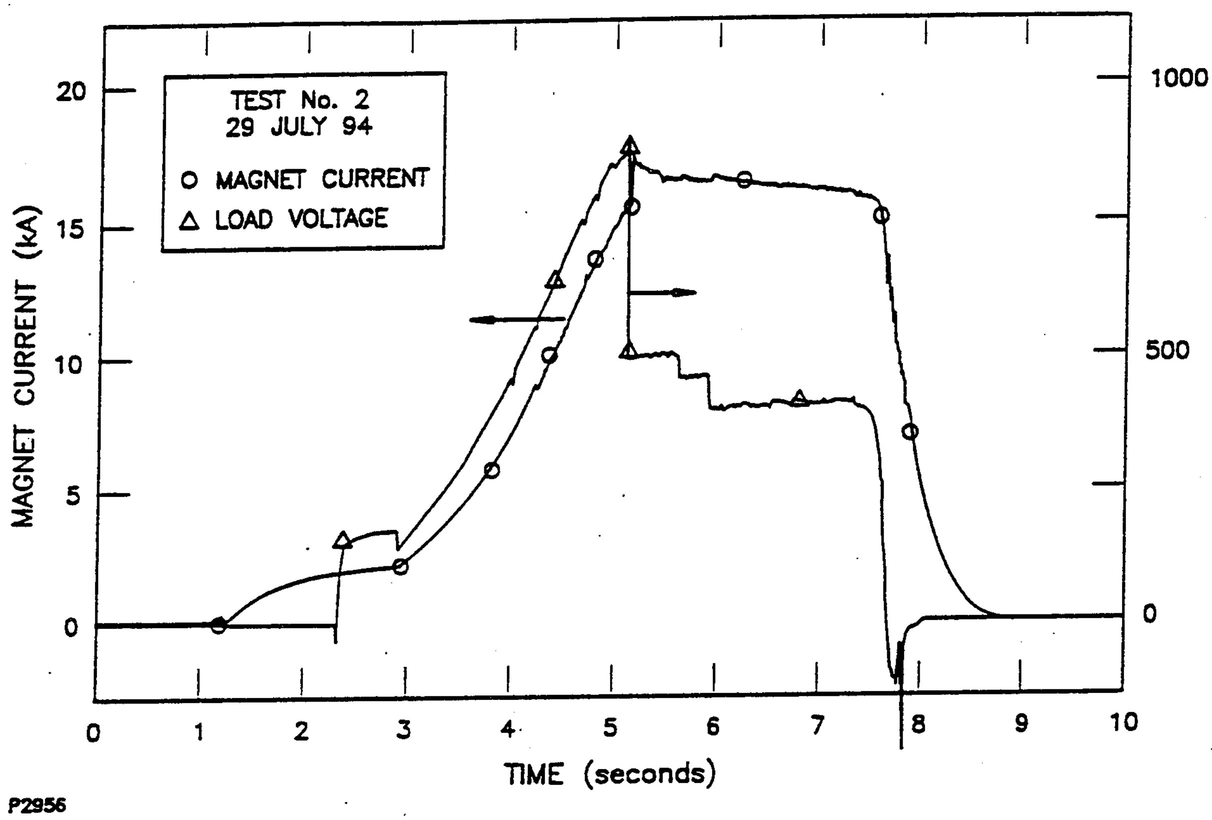


Figure 54 Performance Results from Preliminary Acceptance Test No. 2

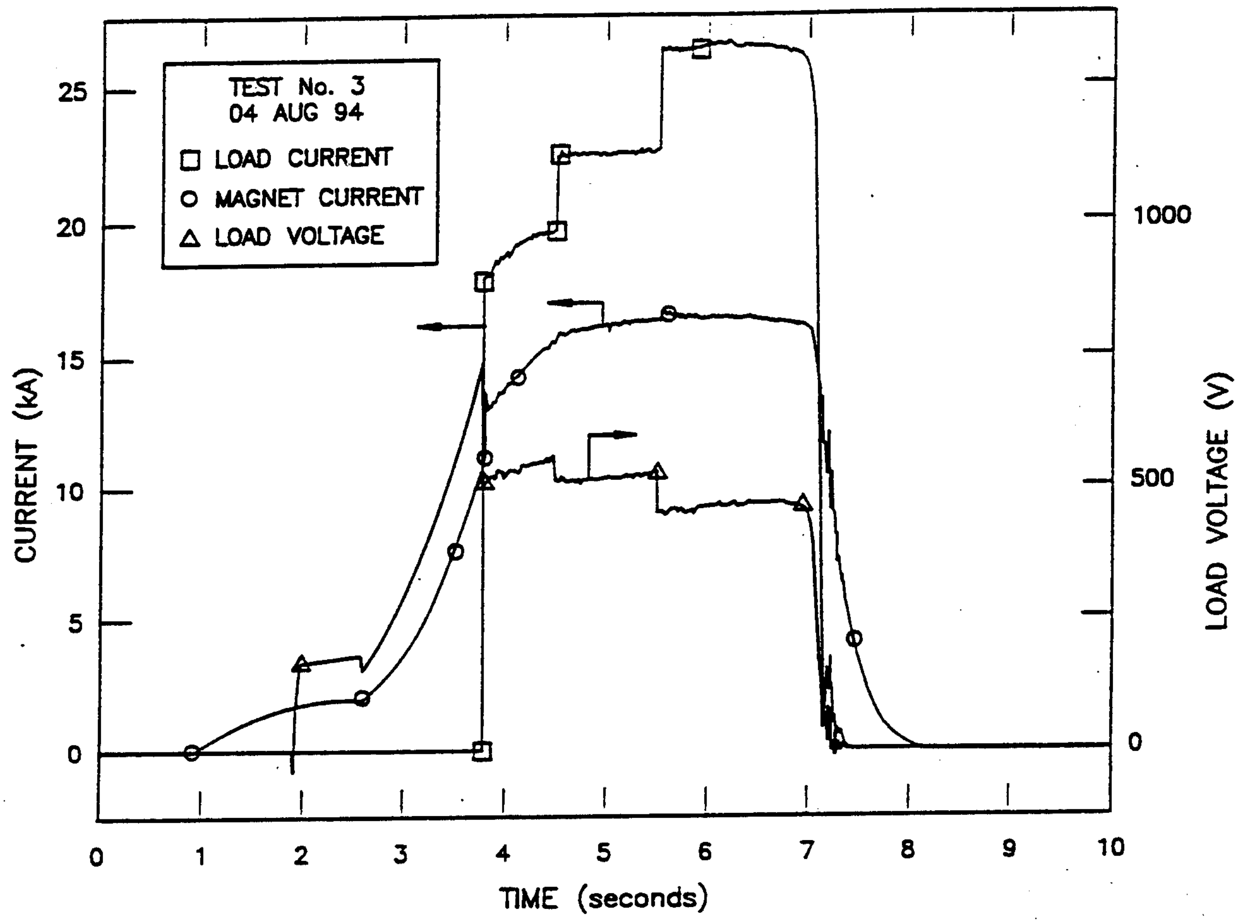


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Figure 55 Performance Results from Preliminary Acceptance Test No. 3

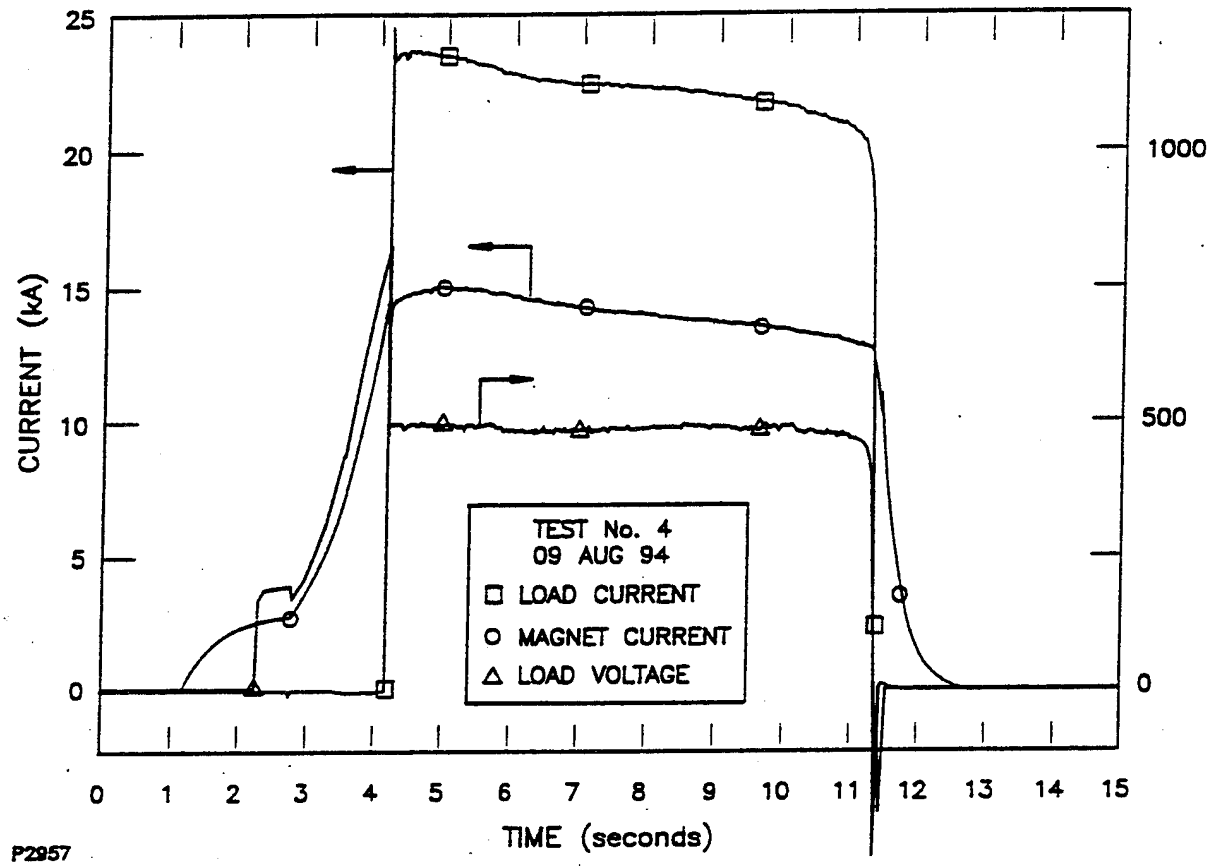

Figure 56 Performance Results from Preliminary Acceptance Test No. 4

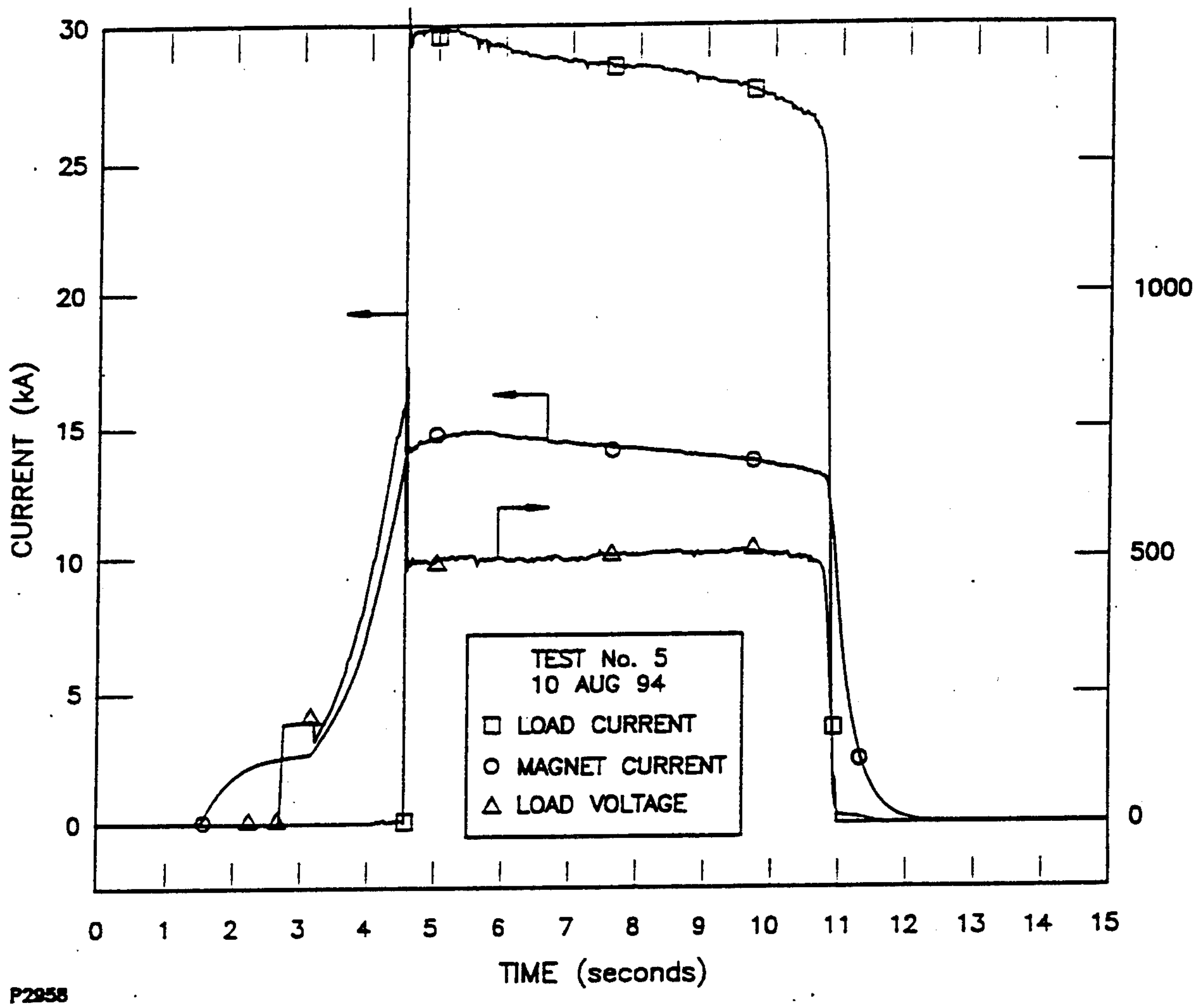

Figure 57 Performance Results from Preliminary Acceptance Test No. 5

6.5.2.9 Discussion of Results

In the first experiment, the limiting value of magnet current of 20 kA was reached. The magnet current time dependence shows that even before the load and the ballast resistance connection, the magnet current began to stabilize near the level reached.

Another anomaly of the first experiment was a premature operation of the dummy load commutators before the planned connection to the channels. Thus, the dummy load resistance value did not change and was equal to 15 mΩ during the entire run.

In the second test, the ballast resistance was connected to the magnet circuit from the very beginning. Thus, the self-excitation process was prolonged by artificial means. The dummy load was commutated in that experiment, as well as in the third one, and its value was equal to 25, 20, and 15 mΩ.

The load current step change corresponds to the re-commutation of dummy load from 25 to 15 mΩ. At these load resistances the maximum output power values were reached of 10.8, 11.7, and 12.1 MW_e, respectively.

The third experiment was performed using the standard BP-10F propellant. The facility operated in standard mode. The maximum output power reached was equal to 12.8/11.9, 14.6/12.6, and 15/13.6 MW_e corresponding to the load resistances 25, 20 and 15 mΩ, respectively.

In the fourth test, the dummy load value was not changed. Its nominal value was set equal to 20 mΩ. The current pulse duration in the load was 7.25 s. The maximum output power in the load was equal to 12.9/11.4 MW_e.

Although the load pulse duration obtained was 1.35 s less than that specified by the design requirements, nevertheless, these test results permitted certain conclusions to be made. For fuel lots with similar burning rates operating at a plasma charge cooling temperature of 0°C and after boring of the critical section area to 80 cm^2, the extended plasma generator operation time will be about 10 s, and the load pulse duration will be about 8.5 s, which matches the design requirements. This conclusion was later confirmed by the results of the acceptance tests in the United States.

In the fifth test, the plasma generator pressure was less than predicted - 46 atm versus 56 atm. The effect may be explained by the fact that the process of thermostating the charges wasn't properly conducted, and the effective thermostating temperature differed from the 35°C that was specified. In comparing the test number five results with previous data where the thermostating temperature was known, the performance results from this test could be interpreted to indicate that the effective thermostating temperature was closer to 20°C.

The self-excitation process was extended and was interrupted by the CMMRS. For the purpose of duplication, the CMMRS has an algorithm for issuing the command for ZM2 operation not only after reaching the specified current value in magnet system, but also after reaching the specified time of excitation process. Therefore, the magnet current value was equal to 14.4 kA compared to the 16 kA that was calculated. Nevertheless, the maximum output power reached in this experiment was as high as 15.1/14 MW_e. The pulse duration was equal to 6.36 s. The comparison of the test results with calculated MHD facility parameters demonstrated their agreement within the 10% accuracy limits of computer codes.

The following remarks on the hardware operation are also appropriate. Because of the extended process of installation, adjustment, and check-out, the CMMRS started its operation with the MHD facility during the fourth test. However, the operational experience in two last tests demonstrated that the CMMRS meets all the technical requirements.

During the tests, exfoliation of the fabric-based laminated gasket of one magnet system coil occurred. This was attributed to poor gluing. The paint on the buses and electromagnet surface was slightly singed by the heat of the exhaust plume. A narrow streak was noted on the base plate surface. This was possibly caused by electrical break-down between plasma flow and the metallic plate. The protective shields were slightly warped.

All of the items mentioned above were modified by Nizhny Novgorod, the manufacturer of these systems, before shipment to the United States. The following specific actions were performed.

1. The new protective shields were manufactured from mineral glass-reinforced plastic. The influence of the exhaust flow of the combustion products on the magnet and current buses was excluded by using these shields. They also prevented the interaction between these flows and the base plate.

2. The glass-reinforced plastic plates IM1-05MP.06.00.101 were manufactured and properly attached.

6.6 SUMMARY AND CONCLUSIONS

The results achieved during the acceptance test program in Russia demonstrated that the performance objectives of the Pamir-3U MHD power system could be achieved. The facility was operated over the full range of specific load resistances, power production modes, and facility operating schemes. Except as noted, test results were obtained for these test objectives. A maximum peak power of 15.1 MW_e and a maximum average power of 14.4 MW_e were obtained.

During the acceptance test program, all elements of the Pamir-3U facility performed as expected. Except for a few minor anomalies discussed earlier in this section, the entire test operation proceeded without any flaws or test delays caused by the equipment. All Pamir-3U MHD power system and facility components were undamaged during the testing and are ready for subsequent tests to be performed. All consumable items performed according to their specifications and lifetime requirements.

The overall results of the test program demonstrated that the Pamir-3U could perform according to specification, that a test rate of three per week can be achieved, and that maintenance and supporting operations can be adequately performed during the non-test periods. The damage that was incurred during the test program has been described in Section 6.5 and the procedure for fixing the problems was identified. The hardware is ready for subsequent shipment to the United States and final acceptance testing.

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7.0 ACCEPTANCE TEST PROGRAM IN THE UNITED STATES

7.1 DESCRIPTION OF TEST SITE

The test site for the acceptance tests in the United States was at the Aerojet facilities, Sacramento, California. This facility occupies approximately 5260 hectares (13,000 acres). About 98% of the site is largely an open area devoted to operations involving hazardous materials, which are primarily liquid and solid propellants/propulsion systems. Approximately 80 hectare (200 acres) are devoted to nonhazardous work including administration, engineering and laboratories, and manufacturing. The overall layout of the facility is shown in Figure 58. All test operations related to the Pamir-3U System tests were conducted in an area designated as "Area 46" which is primarily devoted to testing of solid rocket propulsion systems.

Actual testing of the Pamir-3U System was conducted on Test Stand P-2 which is located within "Area 46" at the center of the circle shown in Figure 58. The approximate layout of Test Stand P-2 is shown in Figure 59. This site was used as the initial unpacking and inspection site for the entire Pamir-3U MHD System as it arrived in five sea containers. Consumable items were segregated from equipment and transferred to other facilities and the CMMRS subsystem was set up in the control room for the test stand (Building 46036). The four main outdoor equipment subsystems were checked out and installed directly on the test stand. These four units of equipment were as follows: (1) the power unit, PU, (2) electrical equipment unit, EEU, (3) initial excitation system, IES, and (4) the dummy load. The Pamir-3U MHD System as installed on the test stand is shown in Figure 60.

Other important test facilities within "Area 46" used to directly support the testing included Buildings 46043, 46038, 46036, and 46035. The layout of these buildings within "Area 46" and their relationship to Test Stand P-2 is shown in Figure 61. Office and meeting facilities for visiting co-workers from IVTAN, Textron, and the U.S. Air Force were provided in Building 33008 located in "Area 33".

Building 46043 is a large covered structure with associated temperature conditioning chambers and is rated for handling large quantities of solid propellants and explosives. It served five main functions during this program:

(1) A receiving, inspection, and storage area for the Class 1.3 (C) and 1.4 (S) explosive consumables utilized in testing (i.e., squibs, igniters, and plasma generator charges)
(2) A receiving, inspection, and storage area for both new and used plasma generator cases and for the channels
(3) An area for assembling plasma generator charges into the plasma generator cases and in some cases for mating plasma generators with channels
(4) A shop area for refurbishing used plasma generator cases and channels
(5) A temperature conditioning facility that was utilized to thermally condition some of the loaded plasma generators and on other occasions to speed the curing of epoxy resins used in refurbishment

Building 46038 is a temperature conditioning facility that is rated for handling large quantities of solid propellants and explosives. It was used during this program to thermally condition some of the loaded plasma generators and/or plasma generator/channel assemblies to specified temperatures in the range of 0 to 42°C.

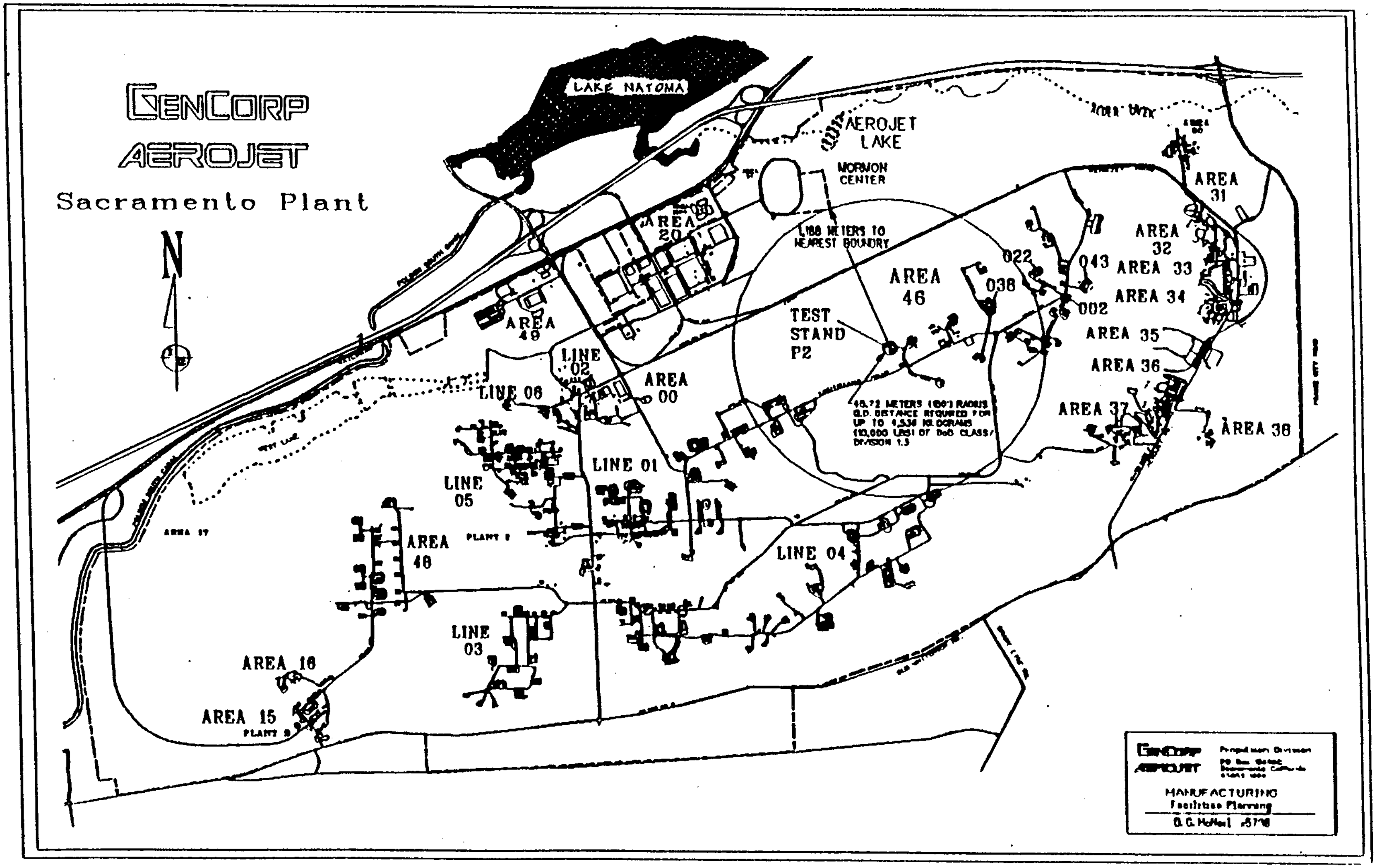

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Figure 58 Plan View of the Aerojet Plant and Facilities, Sacramento, California

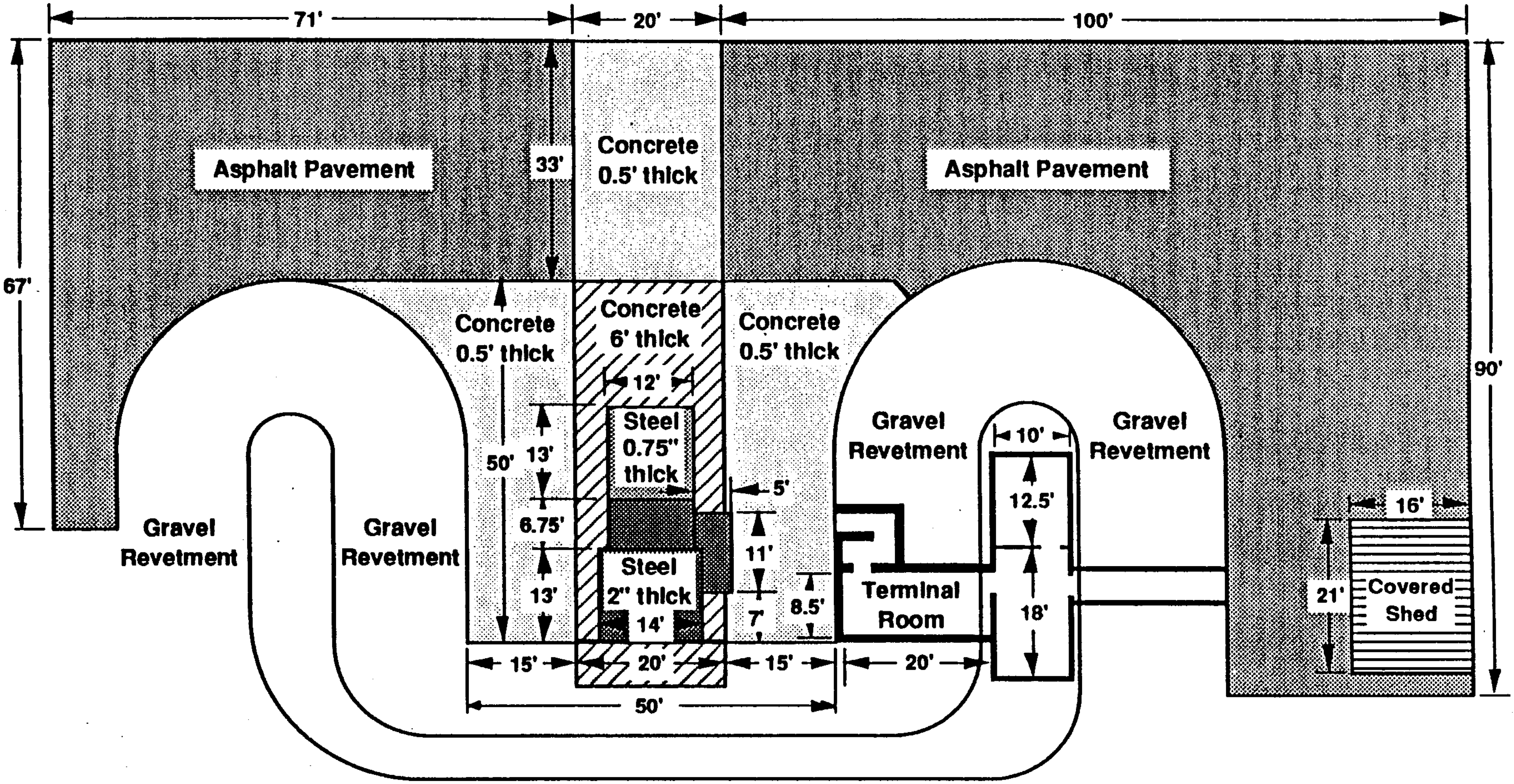

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Figure 59 Plan View of the Aerojet P-2 Test Stand

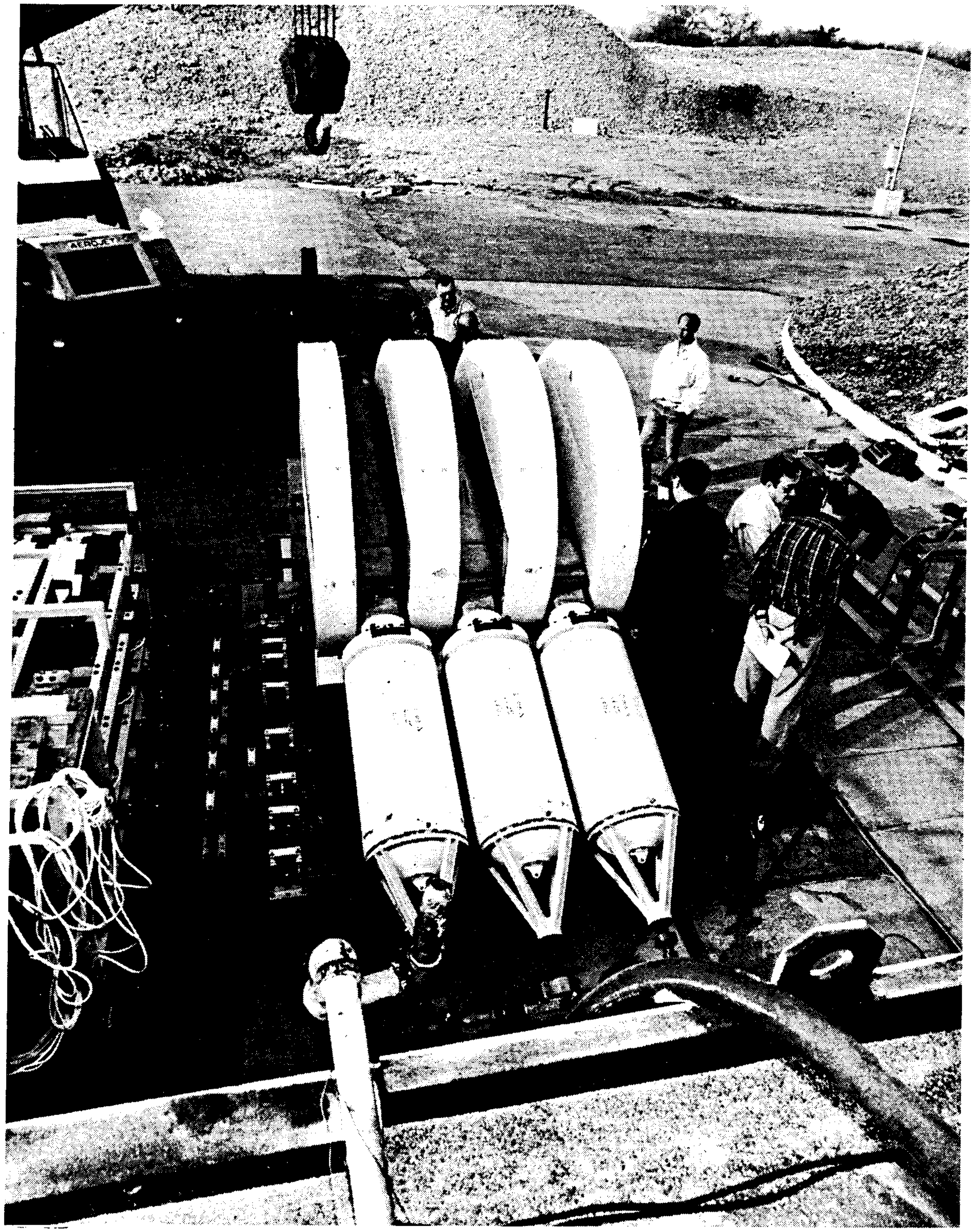

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Figure 60 Pamir-3U MHD Power System Installed on the Aerojet P-2 Test Stand

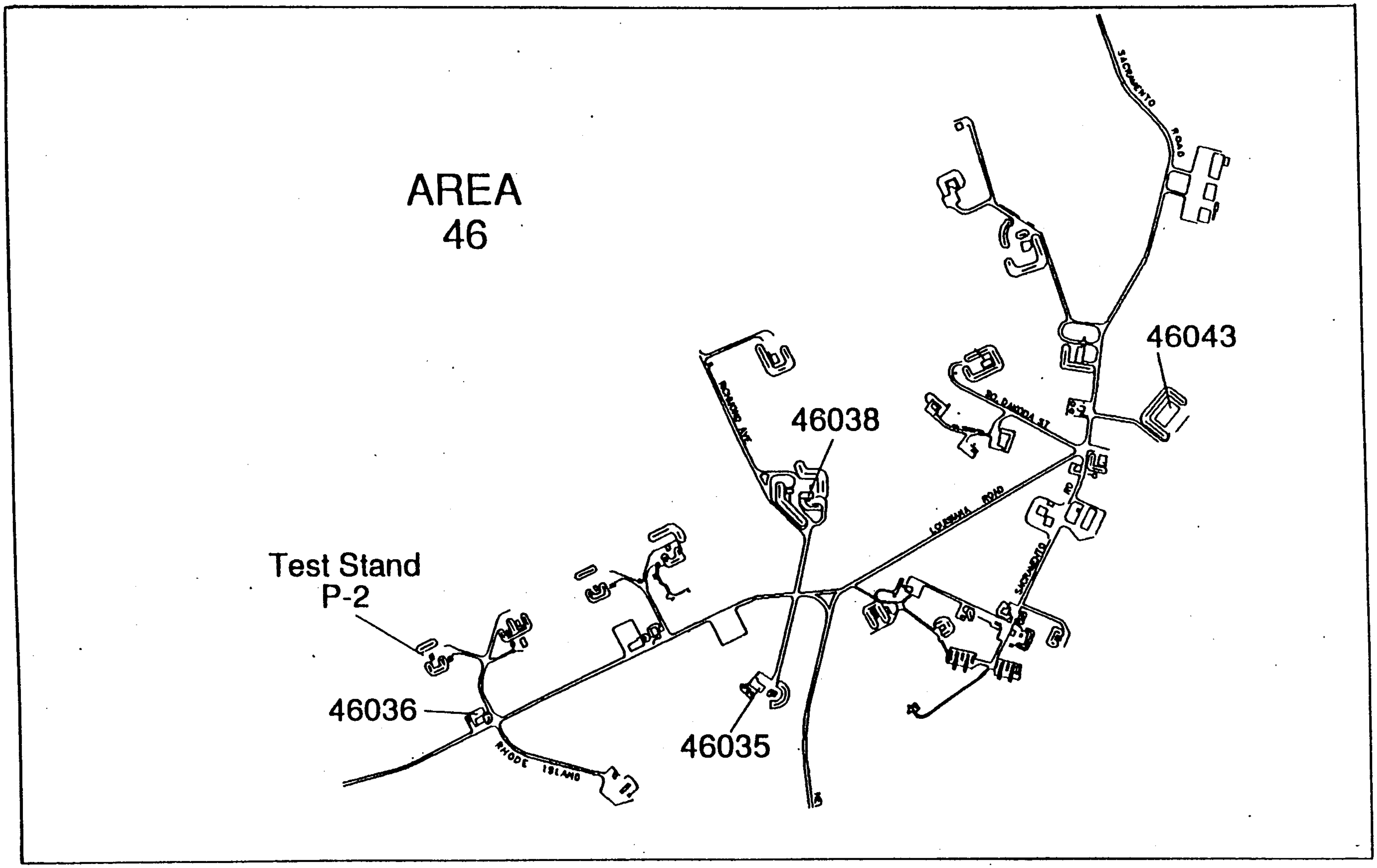

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Figure 61 Layout of the Test Site in Area 46

Building 46036 is a riveted control room/structure dedicated to remote control of tests on Test Stand P-2 and other P-Zone test stands. It provides capabilities to remotely control test firing operations, to observe and record tests on video, and to acquire digital and analog data from solid rocket motor firings. It was used during this program to house the CMMRS subsystem of the Pamir-3U, to electronically communicate with the CMMRS, to provide voice contact with and video observation of Test Stand P-2, to provide overall test control and appropriate area warnings and announcements, and to acquire video recordings of the tests. The autonomous CMMRS provided the primary control, measuring, monitoring, and recording functions for the Pamir-3U tests.

Since Building 46035 had existing, permitted storage capabilities for Class 1.1 explosives, it was used for this program only to store the electric blasting caps, which are Class 1.1 explosives.

7.2 TEST OBJECTIVES

The Acceptance Tests in the United States were performed in pursuit of two main goals:

1) Demonstration of the required performance of the Pamir-3U facility output parameters:

Parameter	Value
Maximum output power	15 MW_e *
Nominal output power	10 - 15 MW_e
Maximum pulse duration	9 ± 0.5 s **
Nominal pulse duration	6 - 6.5 s
Electrical load resistance	20 ± 5 mΩ

* At nominal load resistance values within the range of 15 - 25 mΩ.

** At total output power not less than 10 MW_e, with use of BP-10 propellant at a temperature of +5 °C and GP-77 plasma generators.

2) The training of the Aerojet and Phillips Laboratory teams for the Pamir-3U maintenance and operation.

Training of the Aerojet and Phillips Laboratory team in the United States was performed in several stages. In reality, this training started long before the beginning of the United States Acceptance Test Program. The training began, initially, with the review of the Pamir-3U facility technical documentation and operation manuals submitted to Textron during early 1994.

The first stage of practical training aimed at the practice of maintenance of the Pamir-3U facility was finished successfully during the Acceptance Tests in Russia. Within this portion of the program, the Aerojet specialists became acquainted with the Pamir-3U facility as a whole, as well as with its separate modules, units, and systems. The United States team members watched the processes of the Pamir-3U facility assembly, disassembly, repair, maintenance, and operation. Then, special demonstrations of practical expedients of the Pamir-3U facility maintenance and operation were given. Detailed explanations were given of every stage of the Pamir-3U facility performance: the facility assembly, pre-run assignment, the entire run, post-run disassembly, and restoration. Those stages were fully recorded by photographs and by video recordings.

During the Acceptance Tests in the United States, particular personnel from Aerojet and Phillips Laboratory were appointed to play the role of their Russian counterpart. Then, the most

important items concerning the Pamir-3U facility arrangement and performance as well as the preferable training manner were refined. The training results were discussed by the two teams. Beginning with the fourth and the fifth runs, service of the Pamir-3U facility was progressively transferred to the United States team.

The United States team successfully serviced the Pamir-3U facility for Test Nos. 7 and 8. This fact is evidence of the completion of a successful training program.

7.3 HARDWARE

The main components of the Pamir-3U MHD facility are listed in Table 31.

TABLE 31
MAIN COMPONENTS OF THE PAMIR-3U MHD FACILITY

No.	Component	Designation	Quantity
1.	Power Unit (PU)	IM1-3.01.00.000	1
2.	Electrical Equipment Unit (EEU)	IM1-3.02.00.000	1
3.	Initial Excitation System (IES)	IM1-3.03.00.000	1
4.	Control, Measuring, Monitoring & Recording System (CMMRS)	RAN 36.00.000	1
5.	Dummy Load	KM-1203.00.000	1

The MHD channels, plasma generators and propellant charges used during for the Pamir-3U MHD facility acceptance tests in the United States are listed in Table 32.

TABLE 32
EQUIPMENT USED DURING THE TESTS IN THE UNITED STATES

Test No.	MHD Channel	Plasma Generator (PG) Type No.	Plasma Generator (PG) Case	Propellant Charge Type No.	Propellant Charge Batch	Propellant Charge No.	Post Test Condition
1	1	GP-77	9401	OE-72	6-94-L	7	PG cases and MHD channels need refurbishment
	2	GP-77	9402	OE-72	6-94-L	15	
	3	GP-77	9403	OE-72	6-94-L	5	
2	4	GP-77	9404	OE-72	6-94-L	16	PG cases and MHD channels need refurbishment
	5	GP-77	9405	OE-72	6-94-L	8	
	6	GP-77	9406	OE-72	6-94-L	12	
3	4R1	GP-77	9403R1	OE-72	5-94-L	13	PG cases and MHD channels need refurbishment
	5R1	GP-77	9402R1	OE-72	5-94-L	21	
	6R1	GP-77	9401R1	OE-72	5-94-L	17	
4	7	GP-77	9409	OE-72	6-94-L	11	PG cases and MHD channels need refurbishment
	8	GP-77	9407	OE-72	6-94-L	9	
	9	GP-77	9408	OE-72	6-94-L	10	
5	4R2	GP-77	9404R1	OE-72	5-94-L	3	PG cases need a refurbishment. Operation life of MHD channels is expired
	5R2	GP-77	9405R1	OE-72	5-94-L	10	
	6R2	GP-77	9406R1	OE-72	5-94-L	16	
6	1R1	GP-77	9403R2	OE-72	5-94-L	8	MHD channels need refurbishment. Operation life of PG cases is expired
	2R1	GP-77	9401R2	OE-72	5-94-L	9	
	3R1	GP-77	9402R2	OE-72	5-94-L	5	
7	7R1	GP-77	9408R1	OE-72	5-94-L	18	PG cases and MHD channels need refurbishment
	8R1	GP-77	9407R1	OE-72	5-94-L	11	
	9R1	GP-77	9409R1	OE-72	5-94-L	14	
8	10	GP-77	9411	OE-72	6-94-L	6	PG cases and MHD channels need refurbishment
	11	GP-77	9410	OE-72	6-94-L	4	
	12	GP-77	9412	OE-72	6-94-L	13	

Note:
PG - Plasma Generator
R1 - Test hardware article after first refurbishment
R2 - Test hardware article after second refurbishment

7.3.1 Hardware Condition after the Firing Runs

7.3.2.1 The Power Unit

1) Plasma generators

The firing conditions and condition of the plasma generator cases after the firing runs are given in Table 33.

TABLE 33
PLASMA GENERATOR FIRING CONDITIONS

Test No.	GP-77 Case No.	A* (cm^2)	OE-72 Batch	Charge No.	T °C	Comb P_{av} (atm)	Press P_{max} (atm)	Oper. Time (s)	DA (%)	Post Test Comments
1	9401	73.48	6-94-L	7	35	44.7	47.1	8.5	3.0	1
	9402	73.48	6-94-L	15	35	45.3	48.8	8.5	2.3	2
	9403	73.48	6-94-L	5	35	46.3	49.0	8.5	2.6	3
2	9404	73.48	6-94-L	16	35	45.1	48.4	8.5	3.0	4
	9405	73.48	6-94-L	8	35	46.3	48.7	8.5	3.5	5
	9406	73.48	6-94-L	12	35	47.5	49.4	8.4	1.7	6
3	9403R1	73.48	5-94-L	13	35	44.6	46.8	8.6	2.8	7
	9402R1	73.48	5-94-L	21	35	46.6	48.6	8.5	2.8	8
	9401R1	75.69	5-94-L	17	35	44.2	46.5	8.6	1.0	-
4	9409	73.48	6-94-L	11	42	45.6	48.9	8.3	2.6	-
	9407	73.48	6-94-L	9	42	48.1	50.8	8.3	4.7	9
	9408	73.48	6-94-L	10	42	49.3	51.8	8.3	2.7	10
5	9404R1	80.17	5-94-L	3	0	37.7	33.0	10.4	0.99	-
	9405R1	80.17	5-94-L	10	0	33.8	35.0	10.4	0.92	-
	9406R1	80.17	5-94-L	16	0	34.3	35.7	10.4	1.1	-
6	9403R2	75.69	5-94-L	8	20	37.8	40.3	9.4	1.0	-
	9401R2	74.7	5-94-L	9	20	40.1	41.9	9.3	1.7	-
	9402R2	75.38	5-94-L	5	20	40.0	42.3	9.4	1.7	-
7	9408R1	75.43	5-94-L	18	0	34.0	34.6	10.2	0.97	-
	9407R1	77.58	5-94-L	11	0	34.0	37.9	10.1	0.79	-
	9409R1	75.39	5-94-L	14	0	34.9	37.5	10.1	1.38	-
8	9411	73.48	6-94-L	6	42	46.9	51.3	8.1	3.1	-
	9410	73.48	6-94-L	4	42	46.7	50.2	8.1	2.3	11
	9412	73.48	6-94-L	13	42	46.3	49.6	8.1	2.0	-

A* - throat area;
T - charge thermostating temperature;
Comb. Press - combustor pressure:
P_{av} - average combustor pressure;
P_{max} - maximal combustor pressure;
Op. time - time of the plasma generator operation (time of the OE-72 charge burning);
DA - relative erosion of the throat measured with respect to the initial size of 73.48 cm^2.

Notes:

1) local swelling of the heat protective coating of the front head in two layers of asbestos cloth was present;

2) **a spalling with dimensions of 70 x 90 x 6 mm^3 in the graphite nozzle inlet was observed;**

a crack developed along the support ring;

local swelling in the heat protective coating of the front head in two layers of the asbestos cloth was present;

3) **a spalling with dimensions of 110 x 90 x 5 mm^3 in the graphite nozzle inlet was observed;**

4) **a small crack of 110 mm length developed in the support ring of the back head;**

5) **local spalling with dimensions of 40 x 40 x 5 mm^3 in the graphite nozzle inlet was observed;**

6) **a crack developed in the support ring of the back head;**

local swelling developed of the heat protective coating of the front head in two layers of the asbestos cloth was present;

7) **before the firing run, the back head was replaced with a new (spare) back head;**

8) **before the firing run, the back head was replaced with a new (spare) back head;**

9) **local swelling of the heat protective coating of the front head in two layers of the asbestos cloth was observed;**

10) **a small spalling with a depth of 3 mm was observed in the graphite nozzle inlet;**

11) **a small spalling with a depth of 3 mm was observed in the graphite nozzle inlet.**

The refurbishment of the plasma generator cases was performed according to the requirements of the "Plasma Generator Case GP77 Repair Specifications GP77TU2"[1]. In addition to the procedures described in this document, the following repairs were performed: repair of any cracks on the support ring by gluing a glass cloth impregnated by an epoxy resin; and repair of any spalling in the graphite nozzle inlet using the repair composition for the MHD channel.

None of the repaired parts of the plasma generator case show any evidence of deterioration after subsequent firing runs nor require any further repair after a firing run. In addition, none of the repaired parts had any negative influence on the plasma generator parameters.

2) MHD Channels

After the first firing run, some transverse cracks appeared on the load bearing shell of the MHD channels around the perimeter. The MHD channels numbered one, two, and seven had five, four, and three cracks, respectively. The distance between the cracks was between 180 and 500 mm. The same cracks appeared on the MHD channels numbered four and seven after the second firing run with three and one cracks, respectively. In addition to these cracks, the MHD channels numbered one, seven, and eight had cracks along the glass reinforced plastic shell near

the location of the connection of the front flange with the load bearing shell. The maximal crack width was no more than 1.5 mm.

The appearance of the transversal cracks in the load bearing shell was caused by repeated shrinkage of the glass reinforced plastic caused by its heating after the firing, which is in turn caused by heat redistribution in the MHD channel components. To prevent this effect, the MHD channels were closed at the exit by glass wool within fifteen minutes after finishing the plasma generator operation. The channels were then extracted from the magnet system, which precluded a burn-out of the adhesives inside of the MHD channel and improved its cooling.

The inner surface of the MHD channels had uniform erosion of 1.0 to 1.5 mm for each wall, except for the local area located just after the graphite insert on the upper and lower electrode walls. The area dimensions were 40.50 mm in the flow direction, 40.60 mm in width, and a depth up to 8 mm. The MHD channels numbered four, five, and six withstood three firings and may be used for a later firing run after repair of all areas of the MHD channel. All detected defects were removed during the MHD channel refurbishment. The repair procedures were performed according to "IM112-5 Channel Repair Manual, IM112-5.00.000RM"[1].

3) Other Equipment

There were no repairs or operational anomalies during the operation of the magnet system or other components of the power unit.

7.3.2.2 Electrical Equipment Unit and IES

The electrical equipment unit and the IES operated in the rated modes; there were no repairs or operational anomalies in their operation.

7.3.2.3 Control, Measuring, Monitoring, and Recording System

Some malfunctions in the data channel for measurement of the load voltage were detected during preparation for Test No. 3. After replacement of a faulty transistor, the serviceability of the channel was restored. During acceptance tests, some defects in the data channel for the PG1 pressure measurement were detected. Beginning with Test No. 8, the correct measurements were obtained by the replacement of a pressure transducer and the measuring channel. The PG1 pressure measurement results in the Test No. 1 to Test No. 7 should be considered to be incorrect.

7.3.3 Summary

As a whole, all systems, subsystems, and units of the Pamir-3U MHD Power System operated in the rated mode, without special reclamation.

7.4 TEST PROGRAM

The Preliminary Acceptance Test Program Plan developed during August 1994, included nine tests at the Aerojet test-site in the United States. The tenth test was considered as a reserve. During this time, the three test objectives - maximum power mode, nominal power mode, and maximum load pulse duration mode - were demonstrated. The Program was divided into three phases: Phase I (Training); Phase 2 (Performance); and Phase 3 (Optimization).

During Phase 1 (Training), the entire facility operation was planned to be performed by the Russian team. During Phase 2 (Performance), the facility operation was planned to be performed jointly by a Russian-United States team. The United States personnel would play the role of their

Russian counterparts. During Phase 3 (Optimization), the facility operation was planned to be performed by the United States team under the supervision of the Russian specialists.

The Random Firing Tests carried out during October, 1994, which were discussed in Section 4.1.4, resulted in three specific conclusions:

1) For the 5-94-L and 6-94-L charge batches, for the maximum power mode, the average output power will be at best near 15 MW_e and will not exceed this value. Because of the enlargement of the nozzle throat area during the MHD facility hot-fire testing, the 15 MW_e level is only achievable during the first usage of the plasma generator cases. In all likelihood, the first application of the MHD channel is also essential.

2) Because the plasma charges had not been tested as an integral part of the system, the test data available for these charges were not sufficient to accurately predict output parameters of the Pamir-3U system.

3) As for the nominal power mode, the test data available was sufficient enough to ensure that the requirement could be achieved with the use of restored consumables (MHD channels and plasma generator cases).

A rigid schedule for the Acceptance Tests (three hot-fire runs per week) was established. The schedule accounted for the required duration of several technical procedures, such as thermostating, restoration of channels and plasma generator cases, and natural cooling of the electromagnet.

These factors required the development of a refined Acceptance Test Program in the very beginning of January, 1995. This improved Program was flexible in its general scope. For example, each successive test assignment was made based upon the results of previous tests. This refined Test Program met the requirements of the Statement of Work to test the Pamir-3U facility over the entire range of load resistances and output power levels.

As a consequence, in contradiction to the initial Program of August 1994, Test No. 1 was preassigned to be maximum rather than nominal power mode. Finally, the initial program plan anticipated that, in the case of successful completion of the Test Program, the total number of tests could be reduced by one or two runs.

The final version of the actual Acceptance Test Program is shown in Tables 34 and 35. Except for particular values of ballast resistance and several other particularities, it repeats the refined Acceptance Test Program of January 1995, concerning the sequence of modes and use of consumables, i.e. batch number, and new or restored channels and plasma generator cases. A set of specified consumables, as well as initial preassigned data for each run are given in Table 36.

TABLE 34
ACCEPTANCE TEST PROGRAM SCHEDULE - FINAL VERSION

Test No.	Operation Mode	Dates
	Hot-fire runs of the Pamir-3U performed by the Russian team (Training)	10-17 February 1995
1	Maximum Power Experiment (MP)	
2	Maximum Power Experiment (MP)	
3	Nominal Power Experiment (NP)	
	Hot-fire runs performed by the joint Russian/ United States team (Performance Tests)	20-24 February 1995
4	Maximum Power Experiment (MP)	
5	Maximum Duration Experiment (MD)	
6	Nominal Power Experiment (NP)	
	Hot-fire runs performed by the United States team (Optimization)	27 February 1995 - 1 March 1995
7	Maximum Duration Experiment (MD)	
8	Maximum Power Experiment (MP)	

TABLE 35
PAMIR-3U MHD POWER SYSTEM TEST PROGRAM

		Training			Performance			Optimization	
	Test No.	1	2	3	4	5	6	7	8
MHD Facility	Operation Mode	MP	MP	NP	MP	MD	NP	MD	MP
Plasma Generator	Temperature (°C)	35	35	35	42	0	20	0	42
	Application								
	1st	+	+		+				+
	2nd			+		+		+	
	3rd						+		
MHD Channel	Application								
	1st	+	+		+				+
	2nd			+			+	+	
	3rd					+			

MP - Maximum Power
NP - Nominal Power
MD - Maximum Duration

TABLE 36
PAMIR-3U MHD POWER SYSTEM TEST PARAMETERS
(ALL TESTS USED BP-10F FUEL)

Test No.	Charge Batch	Charge No.	Channel No.	Plasma Generator Case No.	Thermo-stating Temp (°C)	Initial Ballast Resist (mΩ)	Initial Load Resist (mΩ)	Magnet Switching Current (kA)
1	6-94-L	7,5,15	1,2,3	9401 9402 9403	+35	25	20	16
2	6-94-L	16,12,8	4,5,6	9404 9405 9406	+35	16	20	18
3	5-94-L	13,21,17	4R1* 6R1* 5R1*	9403R1* 9402R1* 9401R1*	+35	18	15	14.5
4	6-94-L	9,10,11	7,8,9	9409 9407 9408	+42	8	15	18
5	5-94-L	3,10,16	4R2* 5R2* 6R2*	9404R1** 9405R1** 9406R1**	+0	18	15	12
6	5-94-L	5,2,9	1R1* 2R1* 3R1*	9401R2* 9402R2* 9403R2*	+20	20	25	14.5
7	5-94-L	11,14,18	7R1* 8R1* 9R1*	9407R1* 9408R1* 9409R1*	+0	12	15	***
8	6-94-L	4,6,13	10 11 12	9410 9411 9412	+42	14	15	14.5

Notes:

* The designation R1 and R2 indicates that the consumables (plasma generator cases and/or channels) were used after the first or second repair.

** With a nozzle throat area bored to 80 cm^2.

*** The load was switched on at the very beginning of the run.

7.5 TEST RESULTS

7.5.1 Results of Cold Run Tests of the Pamir-3U MHD Facility in the United States

After mounting the Pamir-3U MHD facility at the operation site according to the Section 4.3 of the Operation Manual IM1-3.00.00.000 OM[2], the Cold runs were conducted.

7.5.1.1 Test Results on Insulation Resistance and Insulation Electrical Strength Between Circuits Having Different Potentials

The results of the tests of insulation resistance and insulation electrical strength between circuits with different potentials are given in Table 37.

TABLE 37
INSULATION RESISTANCE TEST RESULTS

Testing Parameter	Units	Value Specified	Value Actual	Remarks
1. Insulation electrical strength between Electrical Equipment Unit (EEU) bus terminals				
3 and 5	kV, dc	5	5	
3 and 6	kV, dc	5	5	
5 and 6	kV, dc	5	5	
2. Insulation resistance between Electrical Equipment Unit (EEU) bus terminals		Not Less Than		
3 and 5	MΩ	20	700	
3 and 6	MΩ	20	100	
5 and 6	MΩ	20	700	

7.5.1.2 Test Results of Insulation Resistance and Insulation Electrical Strength Between Current Carrying Circuits and the Grounding Device

The results of tests of insulation resistance and insulation electrical strength between current leading circuits and the grounding device are given in Table 38.

TABLE 38
GROUND LOOP INSULATION RESISTANCE TEST RESULTS

Testing Parameter	Units	Value Specified	Value Actual	Remarks
1. Insulation electrical strength	kV, dc	5	5	
Insulation resistance	MΩ	Not Less Than 10	160	with the CMMRS cables disconnected
		10	150	with control and measuring cables connected

7.5.1.3 Results of Excitation Circuit Resistance

The results of excitation circuit resistance tests are given in the Table 39.

TABLE 39
EXCITATION CIRCUIT RESISTANCE TEST RESULTS

Testing Parameter	Units	Value Specified	Value Actual	Remarks
Circuit resistance between the Power Unit (PU) terminals,				
"+" K3 and "-" K1, K2	MΩ	57.5±1.5	58.3	before firing runs
"+" K3 and "-" K1, K2	MΩ	*	64.6	40 minutes after firing run N 7

Note: * - not specified.

7.5.1.4 Test Results in "Cold" Run Mode

The results of the tests of the facility operation in Cold run mode are listed below.

1) The initial excitation current is 2.7±0.1 kA. The specified value is 2.8±0.2 kA.

2) The time of achievement of 95 % stable value of the initial excitation current is 1.6 s. The specified value is 1.6 s.

3) The PG1-PG3 generators start 1.3 s after the KPHB command. The specified value is 1.3 s.

4) The time of the automatic protection device disconnection from the Initial Excitation System (IES) is 1.7 s after the KPHB command. The specified value is 1.7 s.

5) The TM, TK1, TK2, and TN currents register as being present .

6) The KPHB, KPG1-KPG3, KZM1, KQ, K3M2-K3M4, KPY1, and KPY2 commands register according to the specified cyclogram.

7) The operation of the pyrotechnical equipment by CMMRS commands was tested. All pyrotechnical equipment operates according to the specified cyclogram.

7.5.1.5 Conclusions:

The Pamir-3U MHD facility is ready for the firing runs.

7.5.2 Firing Test Results

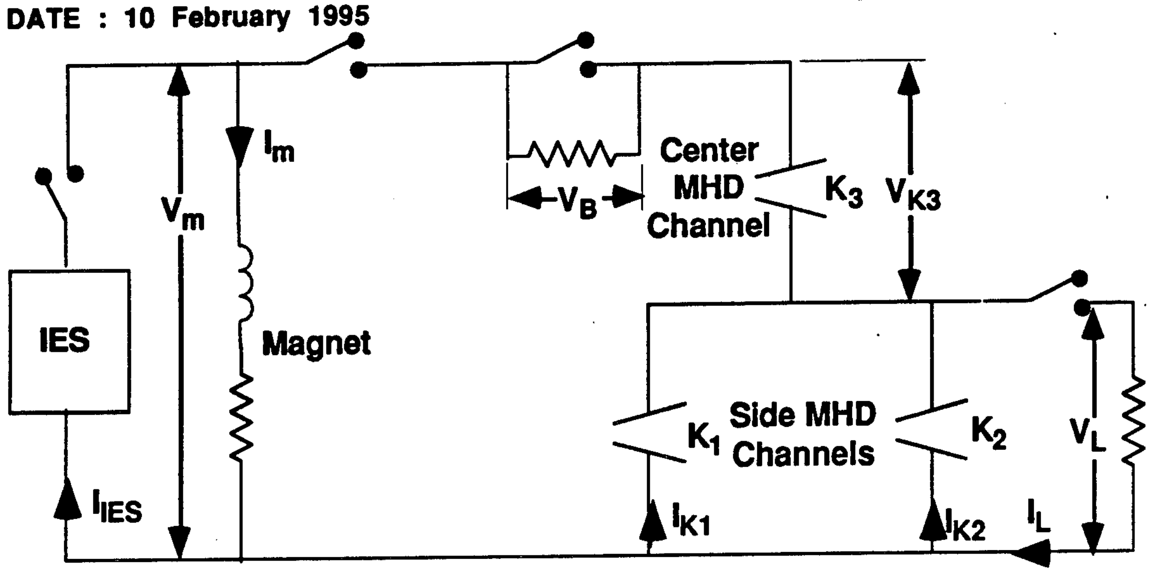
The main test results are given in Tables 40 to 47. In Tables 40 and 41, the "Range" column shows values of electrical parameters, except for output power, for starting and finishing times of the MHD facility load operation. The same column in Tables 42 to 47 shows maximum and minimum values of electrical parameters achieved during the run. Output power values given in the "Range" column of Tables 40 and 41 are obtained in the same manner. In the case of the magnet voltage, V_M, and the channel voltages, V_{K1}, V_{K2}, and V_{K3}, the column with the average data lists two values. The first value is the average value before the electrical load is switched into the circuit, and the second value is the average value after the electrical load is switched into the circuit.

The measuring channel P1 exhibited a malfunction during the Test Nos. 1 to 6. Thus, the data obtained included a systematical error. These data should be excluded from the test analysis. After switching the P1 gauge to a reserve measuring channel, reliable results were obtained.

Figures 62 to 69 show the graphs of the main parameters plotted as a function of time. Figure 70 shows the Pamir-3U MHD power system during operation at Test Stand P-2 at Aerojet. The Pamir-3U parameters achieved in all eight tests are listed in Table 48.

TABLE 40
PAMIR-3U ACCEPTANCE TEST NO. 1 RESULTS

DATE : 10 February 1995



	Peak	Average	Range	Calculated/Measured
R_L, mΩ	23.36	21.68	20-23.36	M
R_M, mΩ	64.6	60.3	56-64.6	M
V_L, V	545	522.5	520-525	M
V_B, V	391	374	391-358	C
V_M, V	1667	830/864.5	0-1661/852-277	M
V_{K3}, V	843	422/717	0-843/723-710	C
V_{K2}, V	834	419/522	0-838/520-525	M
V_{K1}, V	834	419/522	0-838/520-525	M
I_L, kA	25.53	23.75	24.99-22.51	M
I_{K1}, kA	21.33	19.92	21.33-18.51	M
I_{K2}, kA	20.52	19.31	20.52-18.11	M
I_M, kA	16.35	14.93	16.29-13.57	M
P_1, kg/cm²	46.89	44.49	35.8-45.7-41.3	M
P_2, kg/cm²	48.8	46.15	35.6-47.8-42.5	M
P_3, kg/cm²	49	46.2	35.7-47.6-42.8	M
P_L, MW	13.55	12.57	13.32-11.82	C

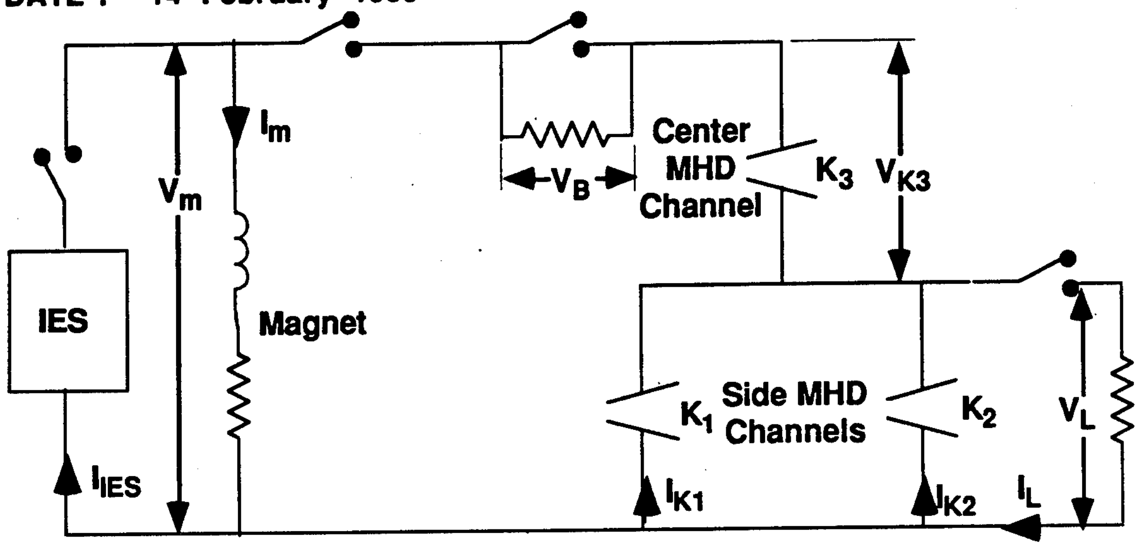
Test Conditions:

Fuel Type = BP-10F
Charge Type = OI-72, 6-94-L
I_{IES} / Final = 2.7 kA
Fuel Temperature = 35°C
Ballast Resistance = 24-26.4 mΩ

$^*A_{AV} = (A_1 + A_2)/2$

TABLE 41
PAMIR-3U ACCEPTANCE TEST NO 2 RESULTS

DATE : 14 February 1995

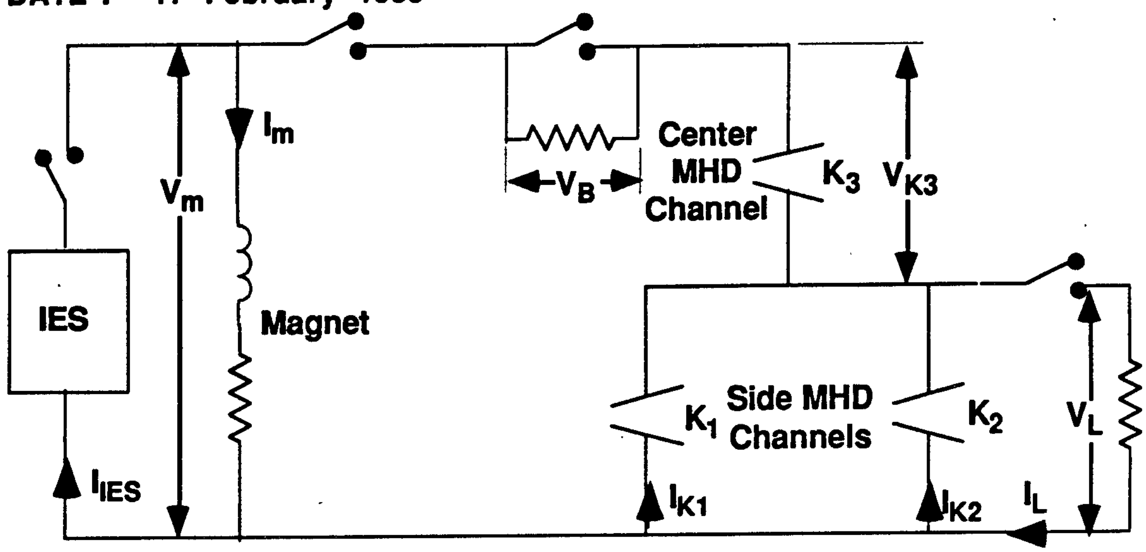


	Peak	Average	Range	Calculated/Measured
R_L, mΩ	23	21.5	20-23	C
R_M, mΩ	65.3	60.6	56-65.3	C
V_L, V	558	535	511-539	M
V_B, V	288	280	271-288	C
V_M, V	1686	979	0-1601/824-984	M
V_{K3}, V	755	650	0-664/575-725	C
V_{K2}, V	938	547	0-937/520-547	M
V_{K1}, V	938	547	0-937/520-547	M
I_L, kA	25.14	24.4	24.93-23.27	M
I_{K1}, kA	22.03	20.49	22.03-19.32	M
I_{K2}, kA	21.44	20.02	21.25-19.43	M
I_M, kA	18.3	16.12	0-18.3-15.1	M
P_1, kg/cm^2	47.9	45.4	36.9-47.6-43.5	M
P_2, kg/cm^2	48.7	45.8	37.7-48.7-43.7	M
P_3, kg/cm^2	49.4	46.86	38.0-49.3-43.6	M
P_L, MW	13.71	13.2	12.76-12.74	C

Test Conditions:
Fuel Type = BP-10F
Charge Type = OI-72, 6-94-L
I_{IES} / Final = 2.66 kA
Fuel Temperature = 35°C
Ballast Resistance = 16 mΩ

TABLE 42
PAMIR-3U ACCEPTANCE TEST NO. 3 RESULTS

DATE : 17 February 1995

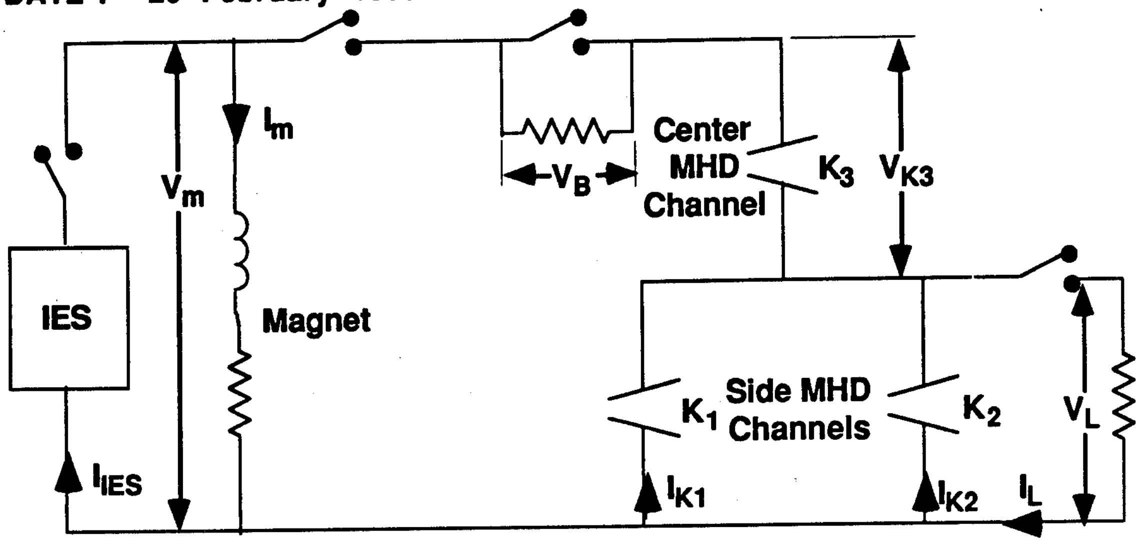


	Peak	Average	Range	Calculated/Measured
R_L, mΩ	17.9	16.7	15.42-17.9	C/M
R_M, mΩ	65.3	60.6	56-65.3	C
V_L, V	480	466	457-480	M
V_B, V	275	260	246-275	C
V_M, V	1630	917	0-1630/880-940	M
V_{K3}, V	745	693	0-745/674-721	C
V_{K2}, V	885	478	0-885/465-489	M
V_{K1}, V	885	478	0-885/465-489	M
I_L, kA	28.56	27.02	25.68-28.56	M
I_{K1}, kA	21.56	20.54	19.58-21.56	M
I_{K2}, kA	22.43	21.19	20.17-22.44	M
I_M, kA	15.3	14.71	13.73-15.32	M
P_1, kg/cm²	46.3	44.0	41.2-46.3	M
P_2, kg/cm²	48.6	46.7	41.4-48.6	M
P_3, kg/cm²	47.1	44.8	33.3-47.1	M
P_L, MW	13.3	12.7	12.1-13.3	C

Test Conditions:
Fuel Type = BP-10F
Charge Type = OI-72, 5-94-L
I_{IES} / Final = 2.72 kA
Fuel Temperature = 35°C
Ballast Resistance = 17.76 mΩ

TABLE 43
PAMIR-3U ACCEPTANCE TEST NO. 4 RESULTS

DATE : 20 February 1995

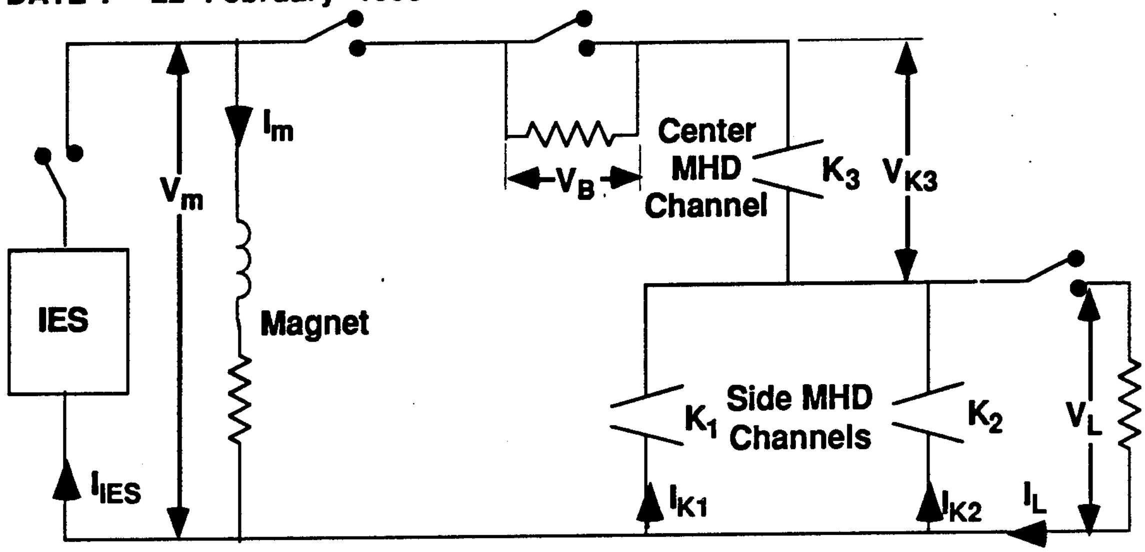


	Peak	Average	Range	Calculated/Measured
R_L, mΩ	17.9	16.7	15.42-17.9	C/M
R_M, mΩ	65.3	60.6	56-65.3	C
V_L, V	508	477	446-508	M
V_B, V	146	134	125-146	C
V_M, V	1783	1069	0-1783/940-1142	M
V_{K3}, V	833	695	0-833/639-752	C
V_{K2}, V	950	492	0-950/457-519	M
V_{K1}, V	950	492	0-950/457-519	M
I_L, kA	28.6	27.9	27.2-28.6	M
I_{K1}, kA	23.8	22.6	21.7-23.8	M
I_{K2}, kA	23.1	22.1	21.6-23.1	M
I_M, kA	18.3	16.7	15.7-18.3	M
P_1, kg/cm²	48.9	45.97	39.1-48.9	M
P_2, kg/cm²	50.4	48.3	40.5-50.4	M
P_3, kg/cm²	51.3	48.4	41.7-51.8	M
P_L, MW	14.57	13.44	12.5-14.57	C

Test Conditions:
Fuel Type = BP-10F
Charge Type = OI-72, 6-94-L
I_{IES} / Final = 2.75 kA
Fuel Temperature = +42°C
Ballast Resistance = 8.1 mΩ

TABLE 44
PAMIR-3U ACCEPTANCE TEST NO. 5 RESULTS

DATE : 22 February 1995

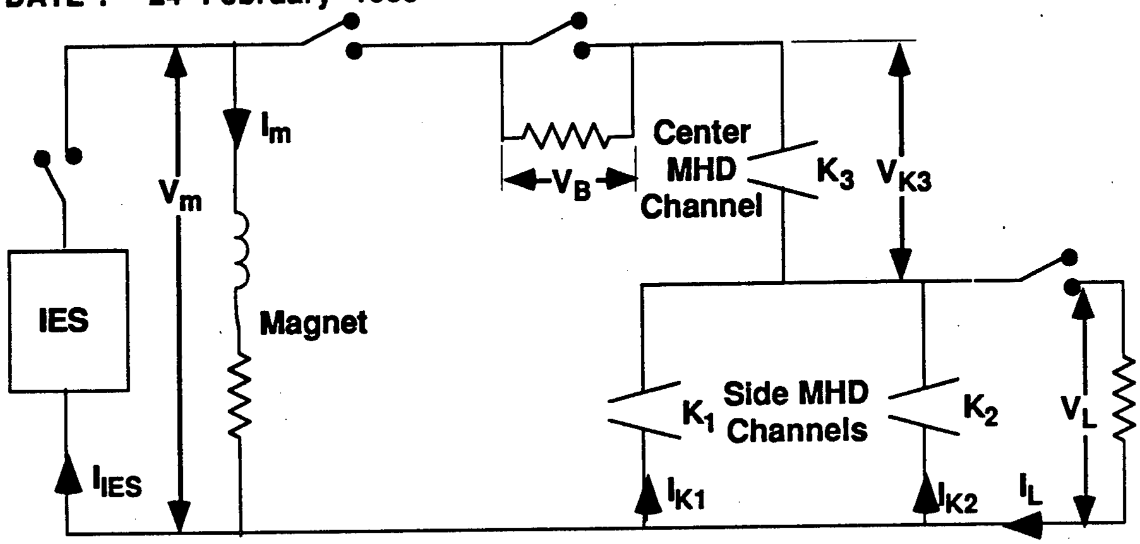


	Peak	Average	Range	Calculated/Measured
R_L, mΩ	17.9	16.7	15.42-17.9	C/M
R_M, mΩ	65.3	60.6	56-65.3	C
V_L, V	433	416	363-433	M
V_B, V	235	226	194-235	C
V_M, V	1257	812	0-1257/784-840	M
V_{K3}, V	626	622	0-609/617-626	M
V_{K2}, V	648	426	0-648/375-443	M
V_{K1}, V	648	426	0-648/375-443	M
I_L, kA	25.02	24.04	22.6-25.02	M
I_{K1}, kA	19.36	18.5	17.4-19.36	M
I_{K2}, kA	19.2	18.47	17.4-19.2	M
I_M, kA	13.1	12.6	0-13.1	M
P_1, kg/cm²	32.9	31.7	26.6-32.9	M
P_2, kg/cm²	35.25	33.8	26.95-35.25	M
P_3, kg/cm²	36.5	34.3	28.6-36.5	M
P_L, MW	10.44	10.04	8.69-10.4	M

Test Conditions: Fuel Type = BP-10F
Charge Type = OI-72, 5-94-L
I_{IES} / Final = 2.7 kA
Fuel Temperature = 0°C
Ballast Resistance = 18 mΩ

TABLE 45
PAMIR-3U ACCEPTANCE TEST NO. 6 RESULTS

DATE : 24 February 1995

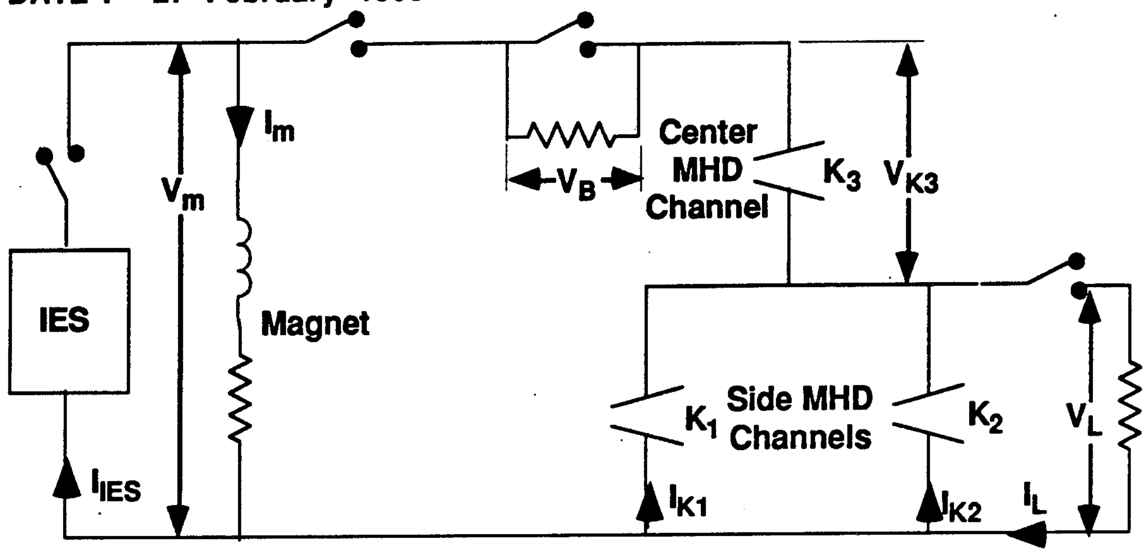


	Peak	Average	Range	Calculated/Measured
R_L, mΩ	29.9	27.45	25-29.9	C
R_M, mΩ	65.3	60.6	56-65.3	C
V_L, V	531	518.7	506-531	M
V_B, V	298	282	262-298	C
V_M, V	1506	893	0-1506/859-924	M
V_{K3}, V	671	625	0-671/603-649	C
V_{K2}, V	835	532	0-835/519-545	M
V_{K1}, V	835	532	0-835/519-545	M
I_L, kA	20.4	19.5	18.4-20.4	M
I_{K1}, kA	17.95	16.9	15.8-17.95	M
I_{K2}, kA	17.88	16.7	15.9-17.88	M
I_M, kA	14.9	14.07	14.9-13.08	M
P_1, kg/cm²	40.2	37.7	31.9-40.2	M
P_2, kg/cm²	41.9	40.2	33.7-41.9	M
P_3, kg/cm²	42.3	40.1	33.1-42.3	M
P_L, MW	10.8	10.15	9.3-10.8	C

Test Conditions:
Fuel Type = BP-10F
Charge Type = OI-72, 5-94-L
I_{IES} / Final = 2.7 kA
Fuel Temperature = +20°C
Ballast Resistance = 20 mΩ

TABLE 46
PAMIR-3U ACCEPTANCE TEST NO. 7 RESULTS

DATE : 27 February 1995

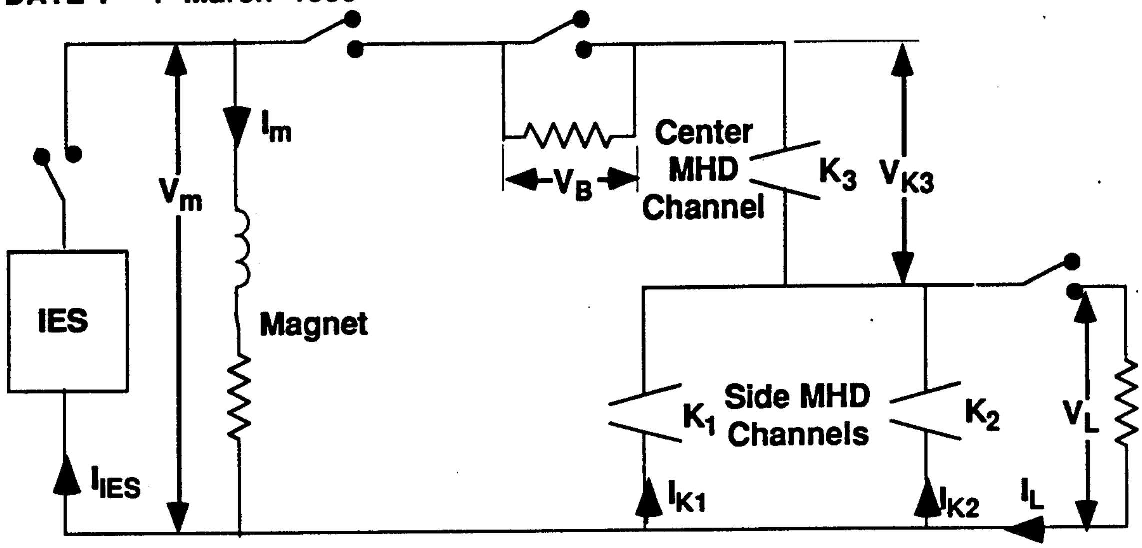


	Peak	Average	Range	Calculated/Measured
R_L, mΩ	18	16.5	15-18	C
R_M, mΩ	65.3	60.6	56-65.3	C
V_L, V	427	407	0-427	M
V_B, V	170	166	0-170	C
V_M, V	919	896	0-919	M
V_{K3}, V	673	654	0-673	M
V_{K2}, V	433	412	0-433	M
V_{K1}, V	433	412	0-433	M
I_L, kA	25.4	25.1	0-25.4	M
I_{K1}, kA	20.1	19.6	0-20.1	M
I_{K2}, kA	20.1	19.4	0-20.1	M
I_M, kA	14.2	13.9	0-14.2	M
P_1, kg/cm²	35.6	34.0	27.4-35.6	M
P_2, kg/cm²	37.95	36.4	29.7-37.95	M
P_3, kg/cm²	37.4	35.9	29.3-37.4	M
P_L, MW	10.84	10.2	9.48-10.84	C

Test Conditions:
Fuel Type = BP-10F
Charge Type = OI-72, 5-94-L
I_{IES} / Final = 2.74 kA
Fuel Temperature = 0°C
Ballast Resistance = 12 mΩ

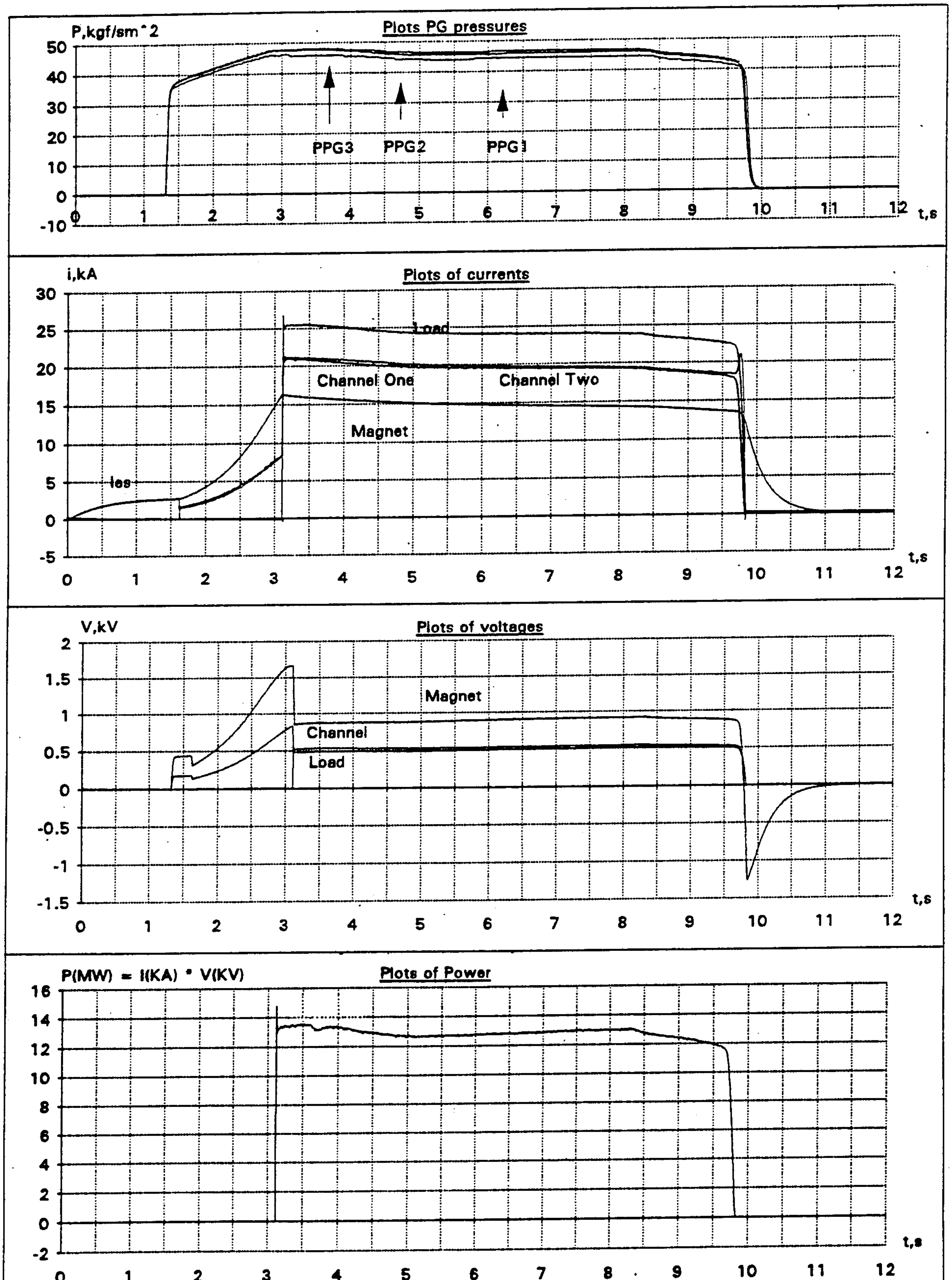
TABLE 47
PAMIR-3U ACCEPTANCE TEST NO. 8 RESULTS

DATE : 1 March 1995



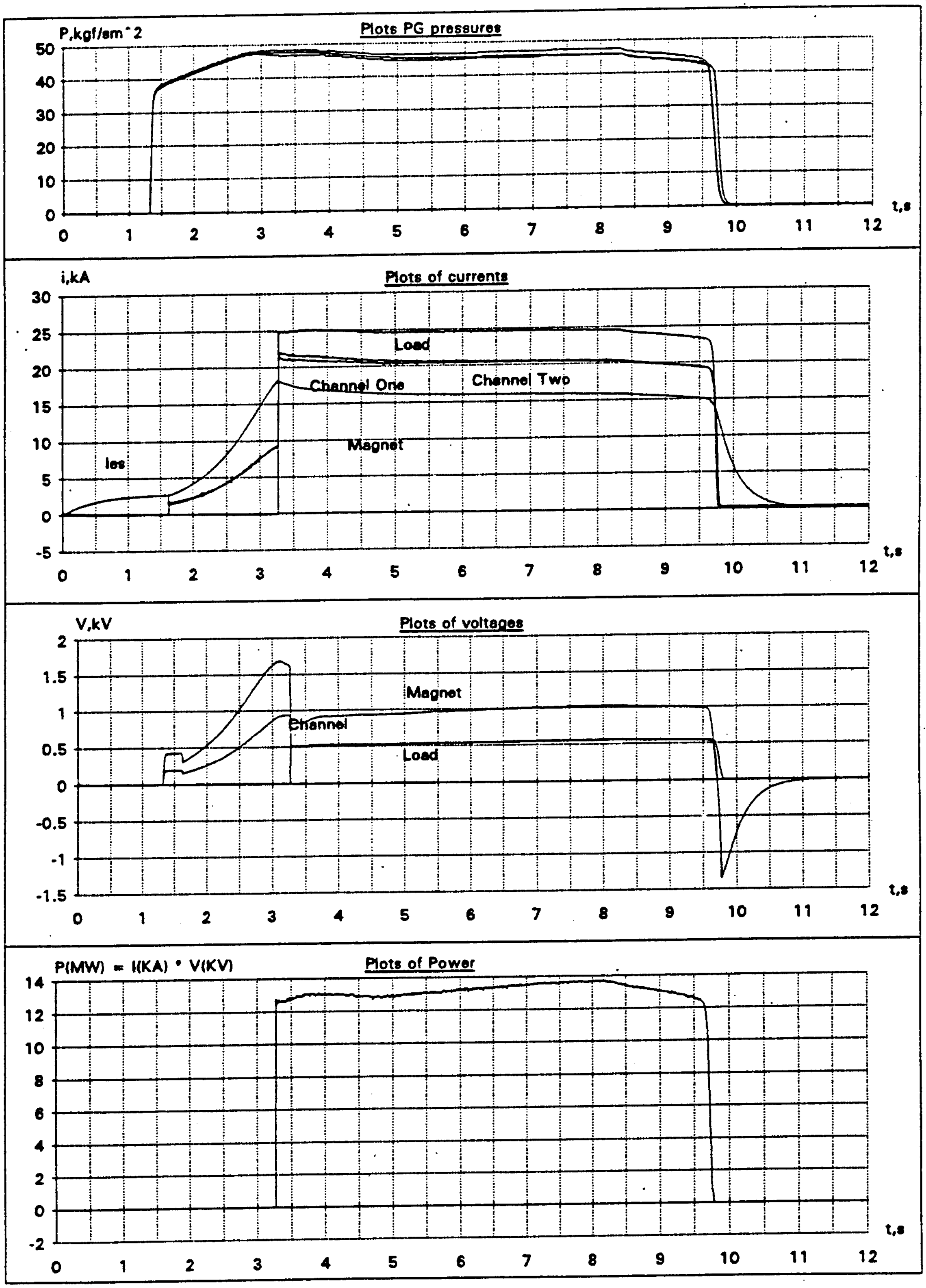
	Peak	Average	Range	Calculated/Measured
R_L, mΩ	18	16.5	15-18	C
R_M, mΩ	65.3	60.6	56-65.3	C
V_L, V	499	472	448-499	M
V_B, V	231	217	203-231	C
V_M, V	1700	1015	0-1700/956-1064	M
V_{K3}, V	812	764	0-812/722-806	C
V_{K2}, V	885	481	0-885/457-507	M
V_{K1}, V	885	481	0-885/457-507	M
I_L, kA	29.97	29.1	27.2-29.97	M
I_{K1}, kA	23.7	22.8	21.3-23.7	M
I_{K2}, kA	23.2	21.8	20.8-23.2	M
I_M, kA	16.5	15.48	14.48-16.5	M
P_1, kg/cm²	50.6	47.9	41.9-50.6	M
P_2, kg/cm²	49.9	47.6	41.5-49.9	M
P_3, kg/cm²	49.9	47.3	41.6-49.5	M
P_L, MW	14.91	13.98	12.5-14.91	C

Test Conditions:
Fuel Type = BP-10F
Charge Type = OI-72, 6-94-L
I_{IES} / Final = 2.7 kA
Fuel Temperature = +42°C
Ballast Resistance = 14 mΩ



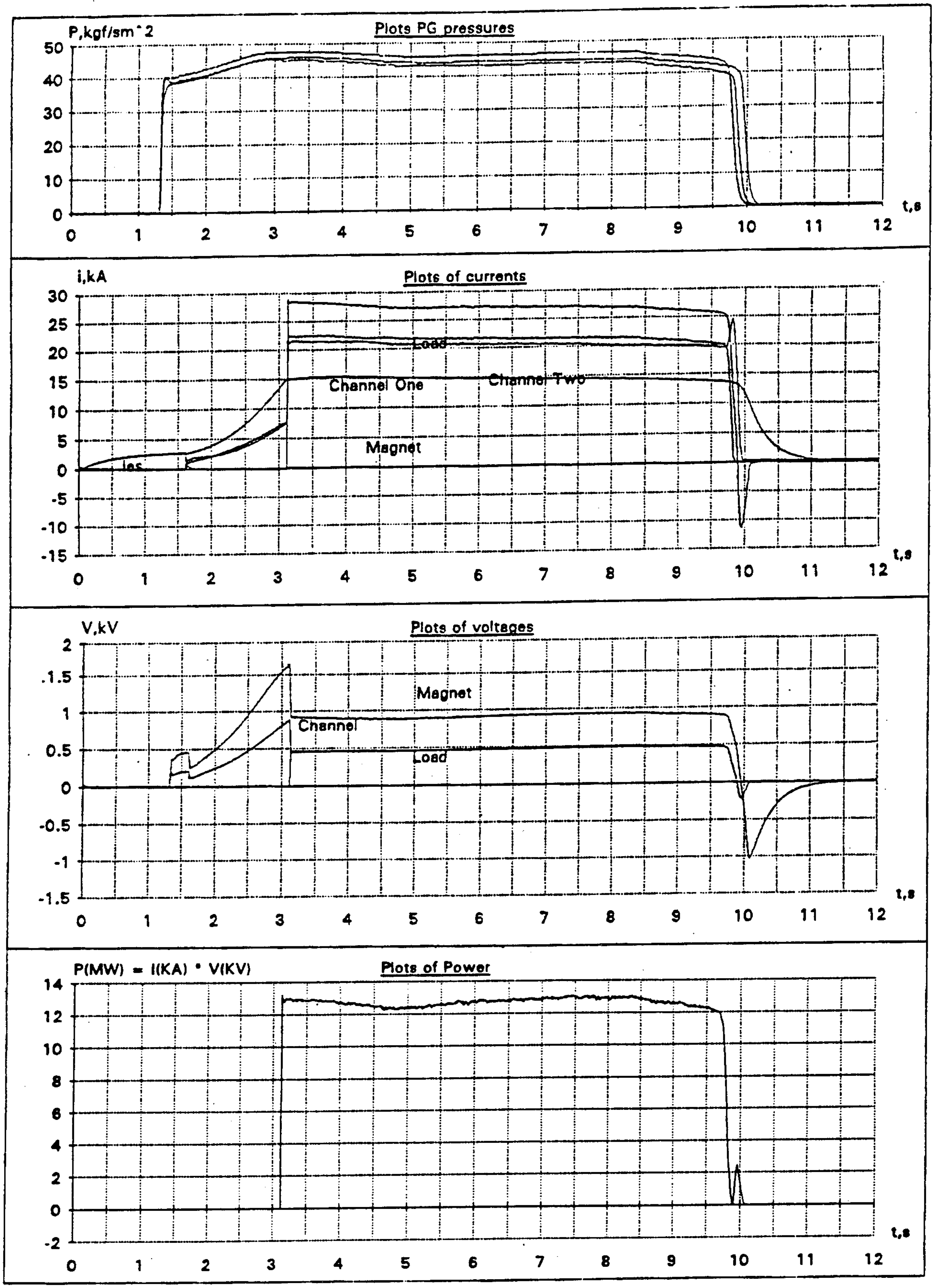
P7592

Figure 62 Performance Results from Acceptance Test No. 1



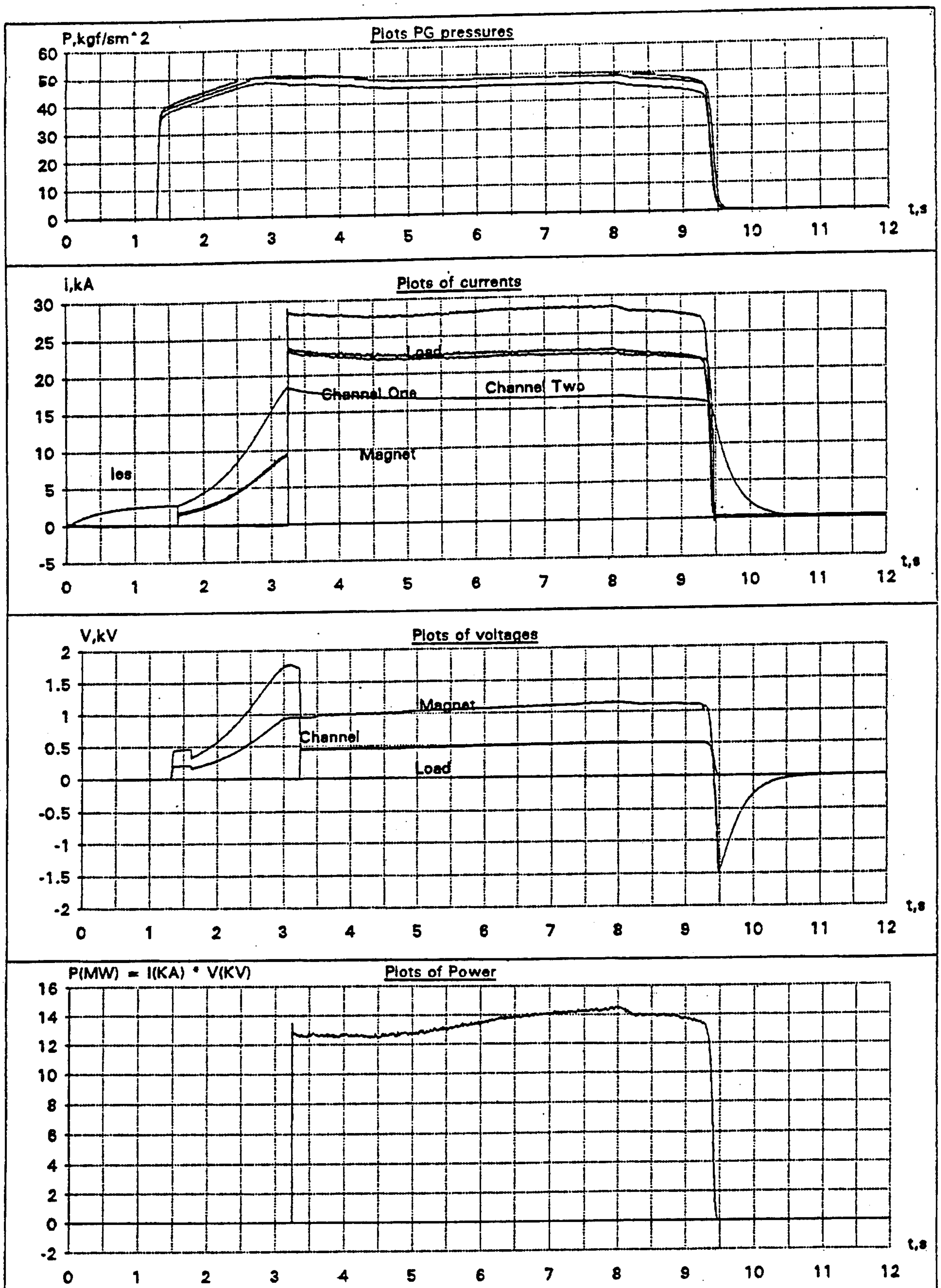
P7593

Figure 63 Performance Results from Acceptance Test No. 2



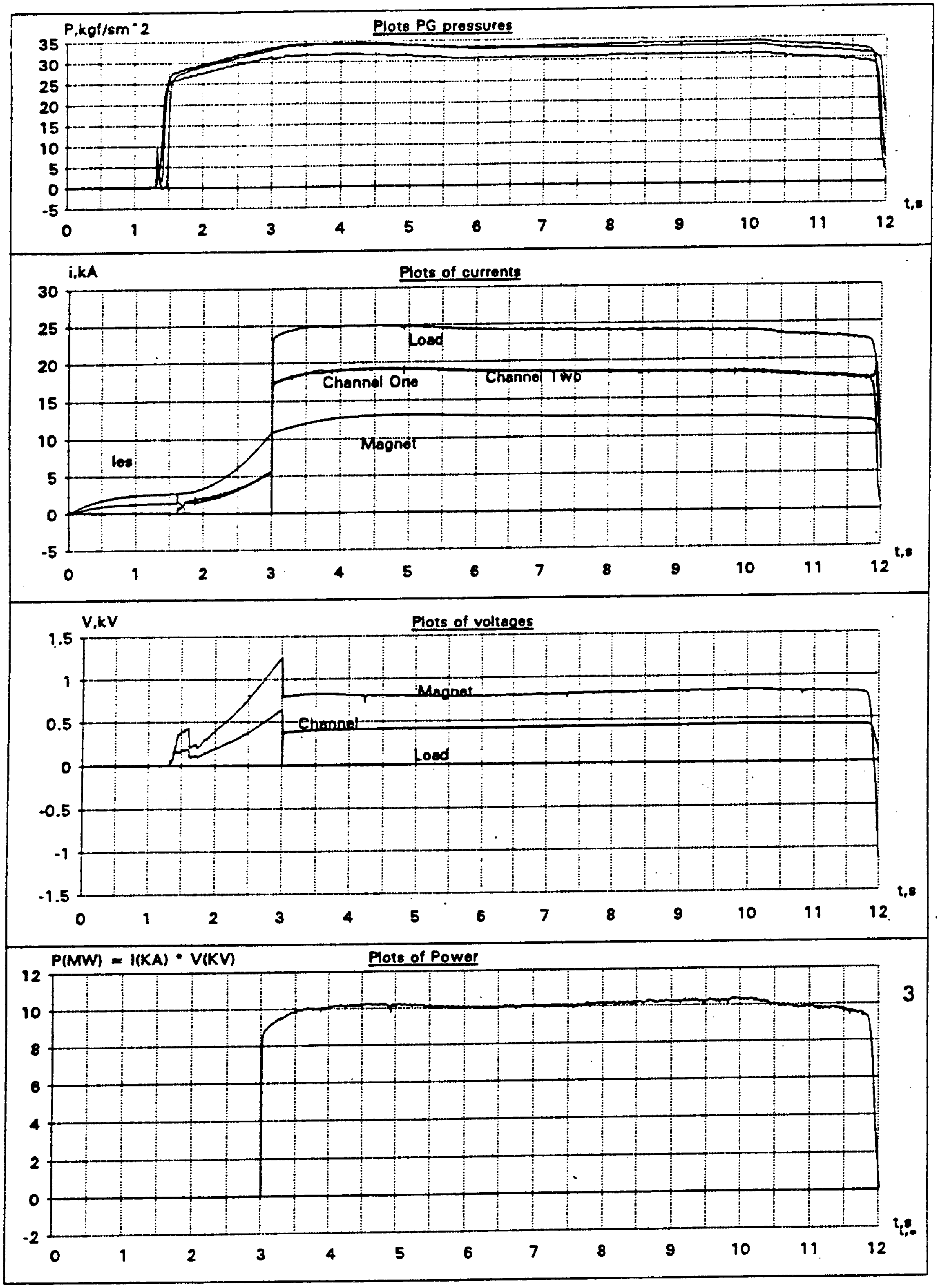
P7594

Figure 64 Performance Results from Acceptance Test No. 3



P7595

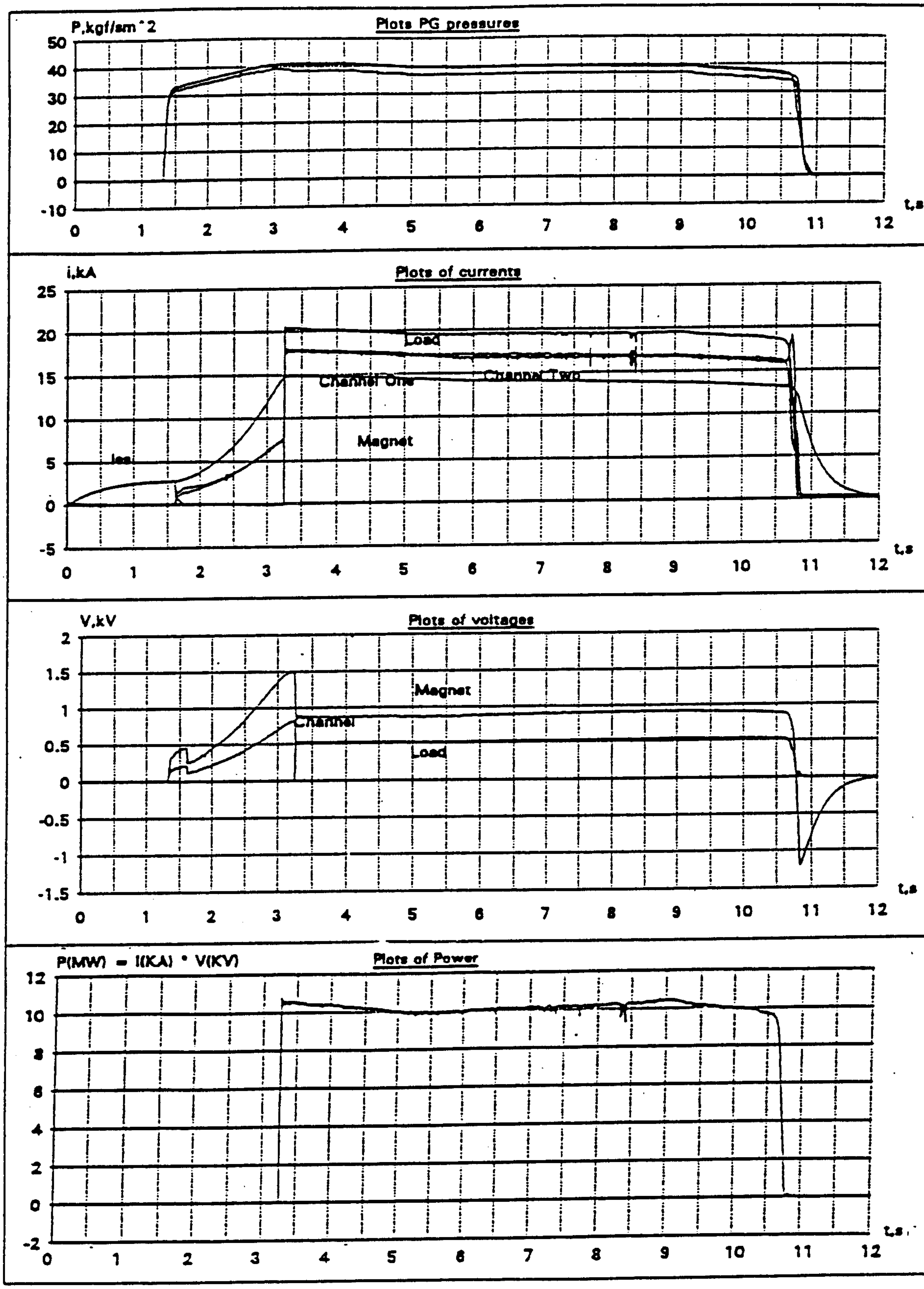
Figure 65 Performance Results from Acceptance Test No. 4



3

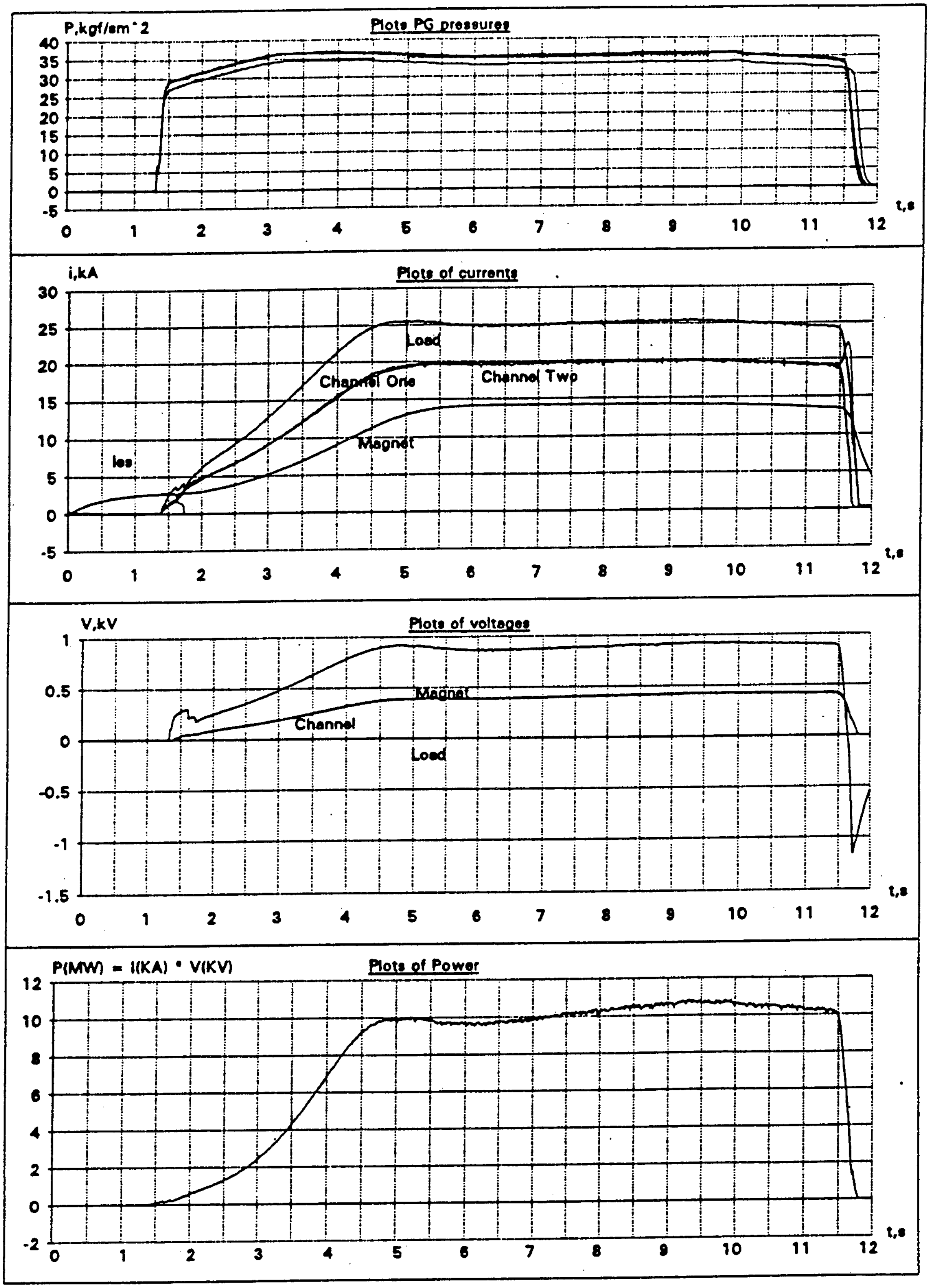
P7596

Figure 66 Performance Results from Acceptance Test No. 5



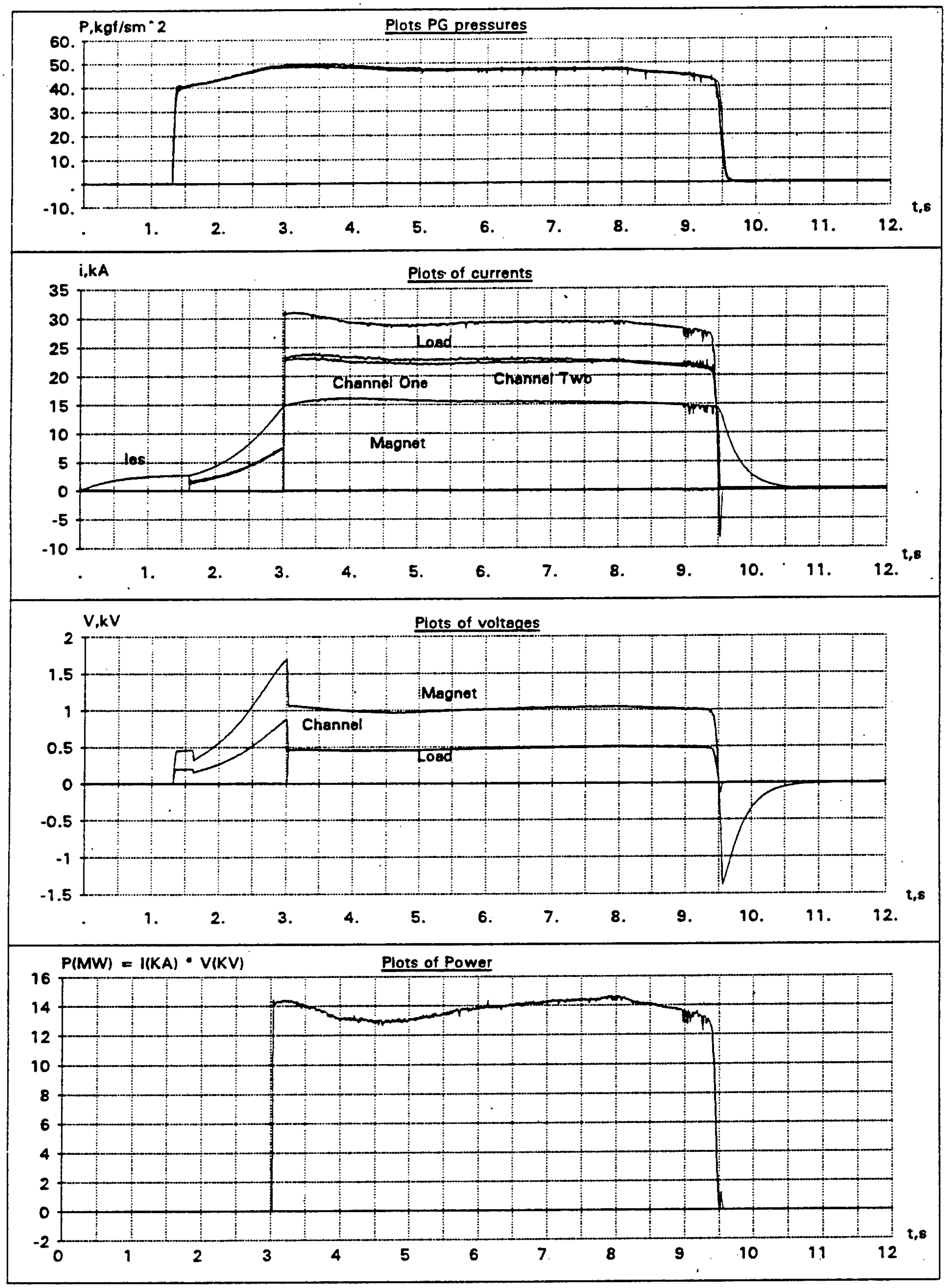
P7597

Figure 67 Performance Results from Acceptance Test No. 6



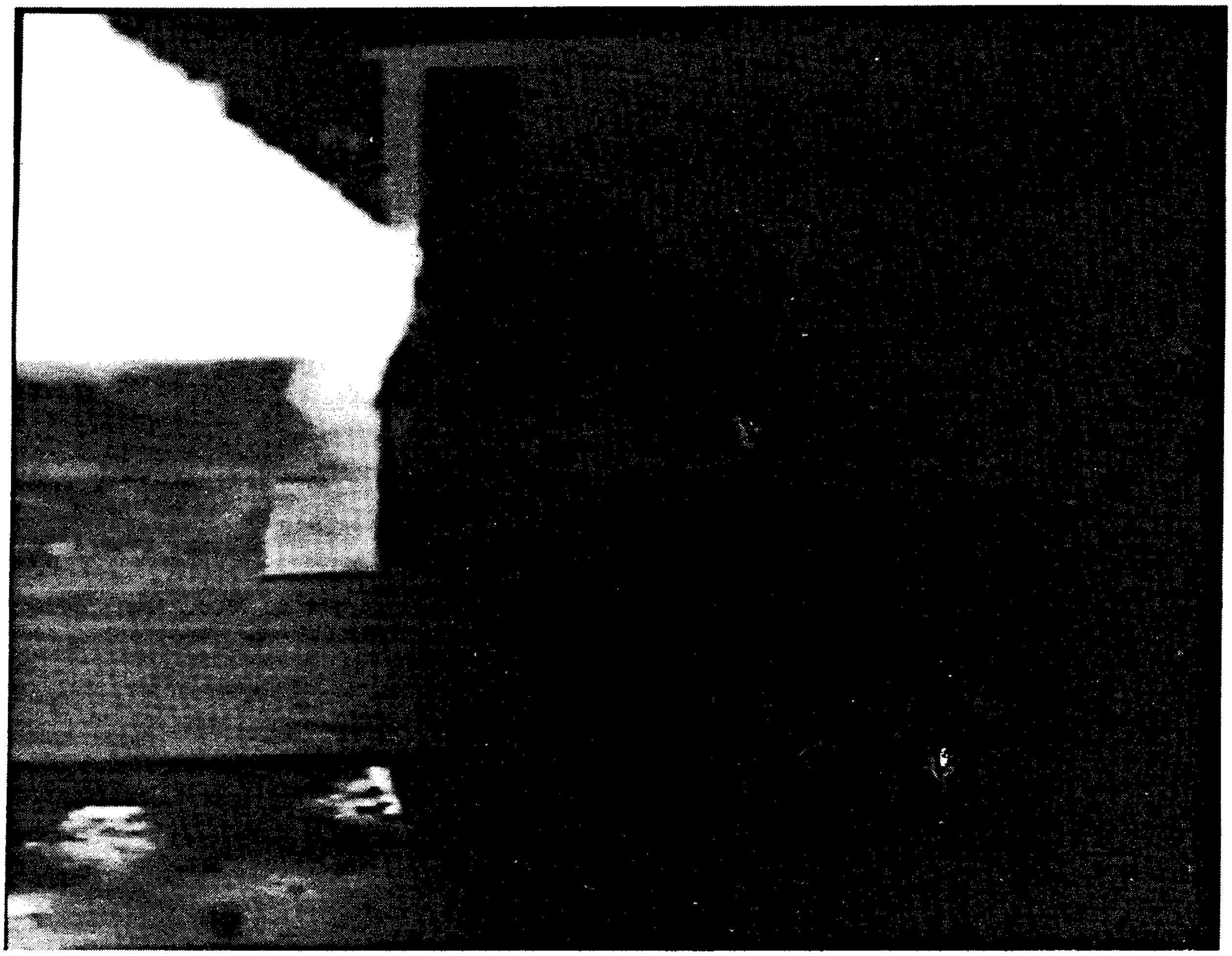
P7598

Figure 68 Performance Results from Acceptance Test No. 7



P7599

Figure 69 Performance Results from Acceptance Test No. 8



P7616

Figure 70 Pamir-3U MHD Power System Hot-Fire Acceptance Test

TABLE 48
SUMMARY OF THE UNITED STATES ACCEPTANCE TEST RESULTS

Test No.	Date of Experiment	Current Pulse Length (s)	Total Load Energy (MJ)	Average Output Power (MW_e)	Max Output Power (MW_e)	Average Magnet Current (kA)	Average Plasma Generator Pressure (atm)	Plasma** Generator Duration (s)
1	02/10/95	6.72	86.0	12.8	13.6	14.9	46.2	8.28
2	02/14/95	6.48	86.8	13.4	14.0	16.1	46.3	8.26
3	02/17/95	6.70	86.8	13.0	13.3	14.7	45.7	8.32
4	02/20/95	6.20	85.6	13.8	14.9	16.7	48.4	7.92
5	02/22/95	8.96	92.3	10.3	10.6	12.6	34.1	10.32
6	02/24/95	7.48	77.8	10.4	10.9	14.1	40.2	9.27
7	02/27/95	10.4	87.8	10.3*	11.0	13.9	36.2	10.20
8	03/01/95	6.43	89.9	14.0	14.9	15.5	47.5	7.97

* Averaging over the quasi-steady state portion of the current pulse.
** Averaging over P2 and P3 in Test Nos. 1 to 6 and over P1, P2, and P3 in Test Nos. 7 and 8 and based on digital records from the computer pressure traces where the time duration is based on the period during which the pressure exceeds 80% of the steady state plasma generator pressure.

The Random Firing Test data, which was presented in Section 4.1.4 for the 5-94-L and 6-94-L charge batches, were not sufficient for accurate prediction of the Pamir-3U output characteristics. Thus, each test assignment was refined on the basis of results obtained from previous tests.

The maximum power mode was demonstrated in Test Nos. 1, 2, 4 and 8. New consumables and charges from the 6-94-L batch were used in these tests for reasons mentioned in Paragraph 7.4. In the Test No. 1, an average output power of 12.8 MW_e, a peak output power of 13.6 MW_e and a load current pulse duration of 6.72 s were obtained with an initial load resistance of 20 mΩ.

To achieve a greater output power in Test No. 2, the magnetic field was increased by decreasing the ballast resistance and increasing the magnet current at the time that the load and the ballast resistance were switched into the circuit.

As a result, an average channel output power of 13.4 MW_e, a maximum channel output power of 14.0 MW_e, and a load current pulse duration of 6.48 s were achieved in Test No. 2 at the same load resistance that was used for Test No. 1. The analysis of the current and voltage curves showed that boundary layer separation appeared to have occurred in Channel 3, which supplies the magnet current, when the magnet current achieved 16.2 kA. This phenomenon was exhibited by magnet voltage decrease. This phenomenon did not occur in Channels 1 and 2, which were supplying the load. Thus, output power in the load was rather stable. The separation phenomenon in Channel 3 primarily impacts the current dynamics in the magnet system, and the boundary layer separation can be eliminated by a variation of the ballast resistance.

The analysis of the first two test results showed that a further increase in output power would only be possible by increasing the pressure in the plasma generators or by an increase in the combustion product mass flow rate. Under real test conditions, this goal could be achieved only by an increase in the plasma charge thermostating temperature.

Thus, the thermostating temperature for Test No. 4 was increased to +42°C. Since this temperature is above the upper limit of +35°C given in the Technical Specification developed by the manufacturer (Soyuz), special approval was requested and received for a thermostating temperature in Test No. 4 of +40 ± 2°C. In this particular case, the plasma charges manufactured as Batch No. 6 satisfied the criteria discussed in Section 3.1.1 for increasing the maximum temperature range to 40° ± 2°C. Because the thermostating facility was capable of precise temperature control well within this limit, the temperature could be set to the maximum without exceeding the temperature limit. In this test at a load resistance value of 15 mΩ, an average channel output power of 13.8 MW_e, a peak channel output power of 14.9 MW_e, and a load current pulse duration of 6.2 s were obtained.

Analysis of the current and voltage curves revealed the beginning of boundary layer separation phenomenon in Channel 3 at a magnet current of 16.9 kA. A load power decrease within the time interval from 3.2 to 5 seconds appears to be explained by the onset of this phenomenon in Channels 1 and 2, which are providing current to the load. This appears to be the case during the Test No. 4 because these two channels were loaded by a lower resistance than in previous tests and their currents were correspondingly more: 15 mΩ compared to 20 mΩ in the Test No. 2, and 23.8 kA compared 22.0 kA, respectively.

On the basis of these results, the last test in maximum power mode (Test No. 8) was carried out at a lower magnetic field to avoid the boundary layer separation. In this test, an average output power of 14.0 MW_e, a maximum output power of 14.9 MW_e, and a load current pulse duration of 6.43 s were achieved under the same test conditions as those in the Test No. 4 - thermostating temperature of +42°C and load resistance of 15 mΩ. Also, special approval was received in advance from Soyuz for the higher thermostating temperature of 40 ± 2°C. However, the increase in the average output power cannot be considered to be substantial. Probably, this is the result of the fact that boundary layer separation occurred in Channels 1 and 2 during Test No. 4 but had no drastic effects. In general, the problem of the effect of boundary layer separation on the Pamir-3U output performance demands further study.

The nominal power mode was demonstrated in Tests No. 3 and No. 6 by the use of repaired consumables and the 5-94-L charge batch. The assembled plasma generators for the Test No. 3 were thermostated at a temperature of +35°C. Under these conditions, an average channel output power of 13.0 MW_e, a peak output power of 13.3 MW_e, and a load current pulse duration of 6.7 s were obtained with a load resistance of 15 mΩ.

The main parameters for Test No. 6 were as follows: thermostating temperature +20°C, load resistance 20 mΩ, average channel output power 10.4 MW_e, peak channel output power 10.9 MW_e, and load current pulse duration 7.48 s. Estimates showed that the average power would be about 12.5 MW_e at a thermostating temperature of +20°C, when using charges from the 6-94-L batch. Thus, the overall range of the average power in the nominal operation mode appeared to be 10 to 13 MW_e for the charge batches tested.

The maximum duration mode was demonstrated in two tests: Test No. 5 and No. 7 using a thermostating temperature of 0°C and plasma charges for batch 5-94-L in both tests. For Test No. 5, the nozzle throat area and the inserts in the accelerator zone were bored out to 80 cm^2. In this test, an average channel output power of 10.3 MW_e, a peak channel output power of 10.6 MW_e, and a load current pulse duration of 8.96 s were obtained with a load resistance of 15 mΩ. Also, in this test, a maximum energy release in the load was achieved of 92 MJ. The total energy generated by the Pamir-3U MHD power system was based on the total integrated net power

produced by the system during the time that the electrical load resistance was connected to the MHD power system.

In Test No. 7, another approach to the maximum duration mode, which is the use of the plasma generator without boring nozzle throat area, was undertaken. In this case, the load and ballast resistances were switched into the electrical circuit from the very beginning of the run, rather than at the end of self-excitation stage. As a result, a load current pulse duration of 10.4 s and a peak output power 11 MW_e were achieved. The average output power within the quasi-steady portion (6.75 s) of the load current was equal to 10.3 MW_e.

By modifying the approach used in Test No. 7, the energy release in the load could be increased by the use of a combined switch-on option: the load could be switched on from the very beginning of the run, while the ballast resistance could be switched into the circuit at the instant when the magnet current achieves its preset value. Thus, the net total energy delivered to the load could be expected to be maximized.

7.6 SUMMARY AND CONCLUSIONS

The results achieved during the acceptance test program in the United States demonstrated that the performance objectives of the Pamir-3U MHD power system could be achieved. The facility was operated over the full range of specified load resistances, power production modes, and facility operating schemes. Satisfactory test results were obtained for these test objectives.

A maximum peak power of 14.9 MW_e and a maximum average power of 14.0 MW_e were obtained. While these power levels were slightly below the 15 MW_e goal, these levels were achieved with plasma charges that were average in performance. Thus, any subsequent tests performed with plasma charges with performance slightly above average would be expected to easily achieve the 15 MW_e net output power objective.

During the acceptance test program, all elements of the Pamir-3U facility performed as expected. Except for a few minor anomalies discussed earlier in this Section, the entire test operation proceeded without any flaws or test delays caused by the equipment. All Pamir-3U MHD power system and facility components were undamaged during the testing and are ready for subsequent tests to be performed. All consumable items performed according to their specifications and lifetime requirements.

The overall results of the test program demonstrated that the Pamir-3U could perform according to specification, that a test rate of three hot-fire tests per week can be achieved, and that maintenance and supporting operations can be adequately performed during the non-test periods. No damage was incurred by any of the system and subsystem components during the test program. The hardware is ready for subsequent transportable power requirements to support testing at a variety of locations.

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8.0 TRANSPORTATION AND MATERIAL HANDLING

8.1 GROUND TRANSPORTATION WITHIN RUSSIA

After the Pamir-3U Facility acceptance tests in Russia were completed and all facility components were finished, the entire facility and consumables for ten power tests were loaded into freight sea containers at the Geodesiya test site for their delivery to the seaport at St. Petersburg, Russia, by truck transportation.

8.1.1 Requirements and Methods

The transportation was arranged according to the requirements for safe delivery of the Pamir-3U facility by truck and sea vessel. The requirements governing this movement are listed in the following documents: *United Nations Identification Codes for Dangerous Goods*; *International Maritime Dangerous Goods Code Book*; *International Agreement concerning the International Carriage of Dangerous Goods by Road;* "Recommendations on Class 1 Dangerous Goods Treatment for Sea Transportation" by Baltic Shipping Company; Russian State Standard 19433-88, *Dangerous Cargo Classification and Marking*; *Rules and Regulations on Safety Transportation of Dangerous Cargo by Truck* by the Russian Ministry of Internal Affairs; and *Temporary Rules and Regulations for Carriage of ZHV-B3, PO-6L, BPT-70, OI-72, UDP2-3 Units, Trotyl, and Ignition Means* by IVTAN.

All measures for the safe transportation of the dangerous cargo were based on test results as well as on the cargo classification and the hazard class and compatibility group.

The Pamir-3U facility includes dangerous goods that belong to Class 1, Subclass 1.1B, 1.1C, and 1.4S and to Class 8, Subclass 8.1 and 8.2. Thus, the main requirement for safe transportation was prevention of emergencies that could impair the life and/or health of personnel as well as the loss or damage of the cargo and/or the vehicle.

The dangerous goods from the Pamir-3U facility were packed so as to prevent any leakage into the transportation crate because of variations of ambient temperature, air humidity, and/or pressure. Internal wrapping and interleave materials as well as the dangerous goods layout were arranged so as to prevent any hazardous movement of the cargo inside the wrapping during its truck and sea transportation.

The dangerous cargo distribution in each container was governed by rules and regulations of the combined transportation according to their compatibility group and danger subclass. The cargo was stamped, marked, and labeled. Danger labels, the cargo name, UN code, IMDG code, and classification codes were applied on the wrappings and packages. Danger labels and the UN code were applied to the containers.

According to the dangerous cargo loading and unloading rules, such work was performed at a specially assigned and equipped area within the loading/unloading site. The special area was supervised by an armed security service and by a specially appointed person authorized in explosion performance and supervision. No extraneous personnel were allowed to be in the special area. Also, special control of the total quantity of the dangerous cargo pieces at the loading/unloading area was provided. The loading/unloading area was arranged according to the requirements of "Unified Safety Rules and Regulations of Explosion Work Performance".

The Pamir-3U facility set was packed into five, 20-foot containers and loaded onto three trailers. The route of travel was from Krasnoarmejsk, Moscow district, to Gatchina, Leningrad district, with subsequent reloading to the St. Petersburg commercial seaport. An armed security group was assigned to accompany the cargo, and a person was appointed responsible for the cargo transportation.

8.1.2 Transportation of Dangerous Cargo

The route was chosen and authorized by the Russian State Traffic Inspection Department. The route selection accounted for the requirements of bypassing settlements, industry objects, recreation zones, and nature and culture reserves. In order to authorize the route, the following documents were submitted to the State Traffic Inspection Department ten days before the shipment: the transportation authorization by the Internal Affairs Office; the transportation route; the certificate for the admission of the dangerous cargo to the vessel; and regulations for safe transportation of the dangerous cargo.

While transporting the Pamir-3U facility set, the trailer traffic was arranged according to the *Russian Rules and Regulations of Road Traffic*, the *Rules and Regulations on Safe Transportation of Dangerous Cargo by Truck*, and the dangerous cargo safety transportation rules contained in the *Temporary Rules and Regulations for Carriage of ZHV-B3, PO-6L, BPT-70, OI-72, UDP2-3 Units, Trotyl, and Ignition Means* by IVTAN. Requirements by the State Traffic Inspection Department concerning the location for loading and parking of the trailers and also traffic restrictions under foggy and/or rainy weather and under snowfall were also taken into account.

The trucks carrying the dangerous cargo were labeled with two information cards fastened on the front and back panels. The front card was placed on the right side of the bumper, the back one was placed on the body of the truck. The cards were not allowed to extend over the clearance limits of the truck nor to overlap the registration number-plates and/or light devices. After unloading the cargo, the information cards were removed.

Only well-experienced drivers who had driven a truck for at least three years, had a driver's license for the proper vehicle category, and had passed special training and medical tests were allowed to drive a truck carrying dangerous goods. In addition to the documents listed in the *Rules and Regulations of Road Traffic*, each truck driver involved in the transportation of the dangerous cargo had a driver's license for the truck to transport the dangerous cargo and a driver's license for transporting dangerous cargo. The transportation route as well as the emergency information sheets were handed to the person responsible for the cargo transportation. A red "Dangerous Cargo" label was applied in the upper left corner of the route lists.

While driving the truck carrying the dangerous cargo, the driver was not allowed to do any of the following: to accelerate quickly; to rapidly apply the brakes; to move the truck with a disengaged clutch, transmission, or engine; to smoke inside the cab; to ignite a fire within 100 m from the location of the truck carrying dangerous cargo; to leave the truck unless a severe emergency existed; to carry any goods not included in the cargo documentation; and to carry any extraneous personnel not relevant to the cargo transportation.

The personnel accompanying the dangerous cargo, that is the person responsible for the cargo transportation and the security service representatives, had certificates authorizing them to participate in the dangerous cargo transportation by the route specified. The names of the accompanying persons were listed in the route lists.

8.1.3 Summary

After the necessary formalities were completed and according to the schedule of departure of the *Haapsalu*, the Pamir-3U MHD facility was shipped from Krasnoarmejsk on 16 December 1994. The Pamir-3U was delivered to the seaport of St. Petersburg on 17 December 1994. During the next five days, it was in storage at a specially guarded loading/unloading site at the sea port. The Pamir-3U was loaded on board the vessel *Haapsalu* on 24 December 1994, and the vessel departed from St. Petersburg on 25 December 1994.

8.2 OCEAN TRANSPORTATION REQUIREMENTS AND METHODS

After finishing the acceptance tests of the Pamir-3U MHD facility in Russia, the facility was disassembled and packed into five sea containers, along with the necessary consumables for ten full power tests. The Pamir-3U MHD system was transported by truck to St. Petersburg, Russia, as described in Section 8.1, and prepared for shipping to the United States. The Baltic Shipping Company of St. Petersburg, Russia, was selected for the transportation of the cargo. The port of destination was Norfolk, Virginia.

The cargo was transported in five standard, 20 foot sea containers. The cargo distribution in the containers is described in the following sections.

8.2.1 Cargo Distribution

8.2.1.1 Container N1

Container N1 had a net cargo mass of 14,254 kg. The contents of the container included the magnet system and electrical equipment. The principal contents of the container are listed in Table 49.

TABLE 49
CONTAINER N1 CONTENTS

Item	Net Mass (kg)	Gross Mass (kg)
Magnet System on a Wooden Skid	10,000	10,000
Metal Cabinet with Electrical Equipment with a Tarpaulin Cover	770	800
Metal Frame	390	390
Dummy Load	2960	2960
Commutation Unit	104	104

8.2.1.2 Container N2

The cargo distribution in Container N2 included equipment with a dangerous cargo of Class 8.2, Type L-20 epoxy resin. The mass of the L-20 epoxy resin was 22 kg. The container net mass was 8800 kg, and the contents are listed in Table 50.

TABLE 50
CONTAINER N2 CONTENTS

Item	Net Mass (kg)	Gross Mass (kg)
Electrical Equipment Unit Including Cables	1950	1950
Twelve MHD Channels	2400	3276
MHD Channel Spares	70	100
Pamir-3U Base Plate	3267	3267
Base Plate	107	107

8.2.1.3 Container N3

Container N3 contains equipment with a dangerous cargo Class 8.1, UN No. 2800, Model 12-CAM-28 storage batteries. The total net mass of the cargo is 6317 kg. All cargo is packed in wooden crates.

8.2.1.4 Container N4

Container N4 contains dangerous cargo of the Class 1.1B, UN No. 0030, electric blasting caps. The net mass of the cargo is 4316 kg. All cargo is packed in wooden crates. Table 51 contains a summary of the contents.

TABLE 51
CONTAINER N4 CONTENTS

Item	Net Weight (kg)	Gross Weight (kg)
Assembly Equipment	65	65
Spare Parts and Accessories	23	93
Expendable Spare Parts and Accessories	270	410
Twelve Plasma Generator Fiberglass Cases	2160	3600
Electric Blasting Caps (8 mm dia.) (Class 1.1B, UN No. 0030, IMDG No. 1257)	2	8

8.2.1.5 Container N5

Container N5 contains dangerous cargo of Class 1.3C propellant charges, Class 1.4S black powder igniters of and Class 1.3C squibs. The net mass of the cargo is 6106.66 kg. The gross mass is 8154.8 kg. The contents are summarized in Table 52.

TABLE 52
CONTAINER N5 CONTENTS

Item	Net Mass (kg)	Gross Mass (kg)
Propellant Charges (418 mm dia.) (Class 1.3C, UN No. 0272, IMDG No. 1245)	6090	8400
Igniters of Black Powder (65 mm dia.) (Class 1.4S, UN No. 0454, IMDG No. 1274)	12	36
Squibs (15 mm dia.) (Class 1.3C, UN No. 0275, IMDG No. 1236)	10	19

8.2.2 Transportation of Dangerous Cargo

The Pamir-3U facility with consumables included the dangerous components listed below:

1) ED-8 electric detonators, electric blasting caps, Class 1.1B, UN 0030, IMDG page 1257, explosive mass of 0.2 kg, net mass of 2 kg, gross mass of 8 kg, 100 pieces in one wooden crate;

2) DE-91 igniters, Class 1.4S, UN 0454, IMDG page 1274, explosive mass of 10.5 kg, net mass of 12 kg, gross mass of 36 kg, 30 pieces in one wooden crate;

3) UDP-2-3 cartridges, power device Class 1.3C, UN 0275, IMDG page 1236, explosive mass of 0.189 kg, net mass of 10 kg, gross mass of 15 kg, 126 pieces in two cans in one wooden crate;

4) OE-72 propellant charges, propelling, for rocket motors, Class 1.3C, UN 0272, IMDG page 1245, explosive mass of 5880 kg, net mass of 6090 kg, gross mass of 8100 kg, thirty charges in thirty wooden crates;

5) CAM-28 batteries, wet, non-spillable, electric storage, Class 8, UN 2800, IMDG page 8121, net mass of 2064 kg, gross mass of 2520 kg; and

6) L-20 epoxy resin, Class 8.2, net mass of 22 kg.

According to IMDG Code, the OE-72 charges, DE-91 igniters, and UDP-2-3 squibs are compatible and were packed in Container N5 as described in Section 8.2.1.5. The ED-8 electric blasting caps are noncompatible with other explosives, and they were packed into Container N1, which is described in item 8.2.1.1. The storage batteries and epoxy resin are noncompatible with other dangerous goods and were packed separately into containers N3 and N2, respectively.

The sea containers for dangerous cargo were selected, prepared, and labeled as well as packed, marked, and filled with the dangerous cargo in accordance with the IMDG code and requirements of Section 49 of the Code of Federal Regulations.

8.2.3 Summary

The Pamir-3U MHD Power System with consumables for ten full power tests in the United States was loaded on-board the Estonian vessel *Haapsalu* and sailed from St. Petersburg, Russia, on 24 December 1994 and arrived in Norfolk, Virginia, on 10 January 1995.

8.3 TRUCK TRANSPORTATION IN THE UNITED STATES

Upon arrival of the Pamir-3U MHD power system at Norfolk, Virginia, the equipment was unloaded from the *Haapsalu*, cleared through United States customs, and loaded onto trucks, which were waiting for the cargo. All hazardous cargo was removed from the ship and placed on the trucks within two hours of the arrival of the ship. This was well within the four hour limitation for time at dockside, which is imposed by the local port authority and the United States Coast Guard.

Because of the mass of the cargo, hazard compatibility, and container loading on the *Haapsalu*, five trucks were required for the transportation of the five sea containers from Norfolk to Sacramento, California. The truck/trailer combinations used for transportation of the cargo were flat bed trailers with air ride suspension. Transportation of the cargo was performed in compliance

with all Department of Transportation and State Regulatory Requirements. The existing permits and authorizations held by the trucking company, Ranger Landstar, were sufficient for the transportation of this cargo.

The five sea containers arrived at Aerojet during the period of 16 to 20 January 1995. The hazardous trucks arrived first with the non-hazardous cargo arriving later. Because of the nature of the contents, the hazardous cargo delivery was first because those trucks drove to their destination without stopping. The non-hazardous cargo carrying trucks were permitted to stop during their transit. All cargo arrived at Aerojet in Sacramento, California, without incident and without any visible container damage.

8.4 MATERIAL HANDLING AND TEST SETUP IN THE UNITED STATES

Prior to handling and setup of any of the equipment or consumable items associated with the Pamir-3U MHD System in the United States, the personnel involved in the testing in the United States were familiarized with the system and with the documentation describing the Pamir-3U System. Familiarization with the equipment, its arrangement, and methods of handling occurred during preliminary acceptance tests of the Pamir-3U system in Krasnoarmejsk, Russia, during August 1994. Aerojet also independently thoroughly evaluated all relevant health, safety, hazard, and permitting issues related to testing the system in the United States, and specifically at the Aerojet site. These various issues and requirements are discussed in Section 8.5. New procedures were prepared by Aerojet where procedures provided to Textron Defense Systems by IVTAN were considered to be incomplete or less stringent than that required to satisfy the Aerojet health and safety directives or mandates from outside governmental jurisdictions.

All the equipment and consumable materials constituting the Pamir-3U MHD System arrived at the Aerojet test site during the period of 16-20 January 1995. The Pamir-3U System was contained in the five sea containers, which were transported by trucks from the port of entry, Norfolk, Virginia. Upon arrival at Aerojet, the sea containers were officially received, off-loaded from the trucks, and placed on the apron of the P-2 test stand. Five support personnel from IVTAN and representatives from Textron Defense Systems and the U.S. Air Force arrived at the Aerojet test site on 23 January 1995. A second group of nine IVTAN personnel arrived on 30 January 1995 to facilitate the complete system installation, checkout, and testing. The visiting personnel from IVTAN and other representatives were introduced to the Aerojet personnel involved in the testing. Operating guidelines at the Aerojet test site and required health and safety training were provided to the IVTAN personnel and to representatives from Textron and the U.S. Air Force. Following an overview of the work plan for the testing activity, Aerojet test personnel and the first group of IVTAN support personnel began the unloading operations.

The unloading operations were performed by the joint IVTAN-Aerojet test team under the direction of IVTAN in accordance with standard procedures defined by IVTAN[1] and special supplemental procedures prepared by Aerojet.[3] IVTAN provided on-the-job training to Aerojet test personnel and to U.S. Air Force observers during these operations. Unloading involved the following steps: (1) breaking the container seals and opening the containers, (2) removal of cribbing and unloading the various shipping boxes and assemblies, (3) taking inventory of the items shipped, (4) inspection for shipping damage (no damage found), and (5) distribution of the equipment, tools, and supplies to four primary locations. The distribution of the various items and their associated spares, tools, and parts is listed in Table 53.

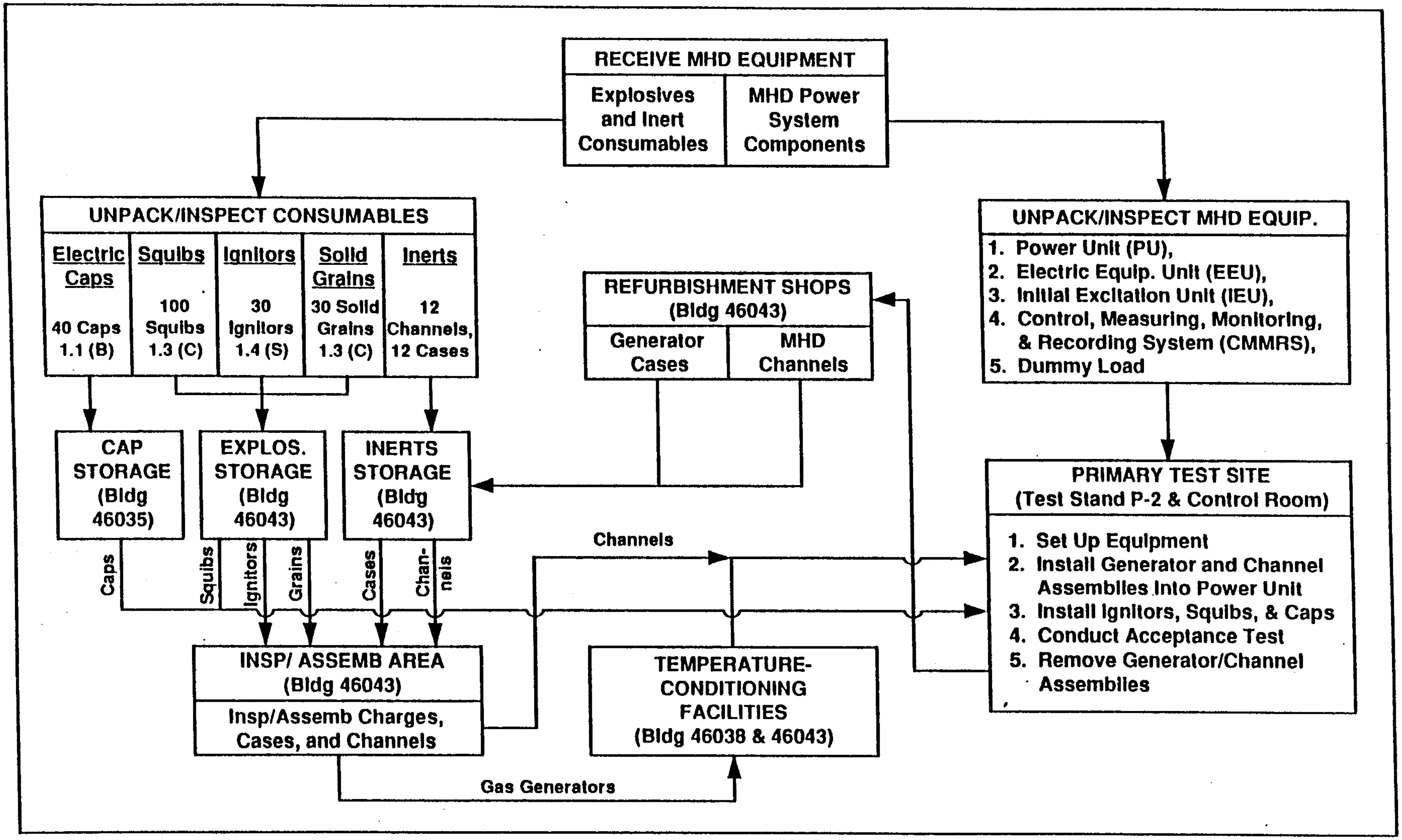
TABLE 53
DISTRIBUTION OF THE PAMIR-3U MHD POWER SYSTEM EQUIPMENT

Location	Equipment
P-2 Test Stand	MHD Power Unit (PU), EEU, IES, dummy load, systems
Bldg 46036 (Control Room)	CMMRS
Bldg 46043	Plasma charges, igniters, squibs, gas generator cases, channels
Bldg 46035	Electric blasting caps

The overall handling scheme and flow of equipment and consumable materials is summarized in Figure 71.

Installation of the Pamir-3U on the test stand involved a series of operations during which IVTAN provided on-the-job training to Aerojet test personnel and to U.S. Air Force observers. These operations were performed by the joint IVTAN-Aerojet test team under the direction of IVTAN in accordance with standard procedures defined by IVTAN[1] and special supplemental procedures prepared by Aerojet.[4] The installation operations included the following steps:

(1) Placement, leveling, bolting, and welding of the MHD power unit base plate on the test stand deck plate
(2) Attachment of the thrust take-out assemblies to the base plate
(3) Installation of the magnet assembly on the base plate and alignment of magnets
(4) Activation of the Initial Excitation System (IES) - cleaning, filling, and charging of 72 batteries and installation of 60 of the batteries and the battery charger into the IES cabinet
(5) Positioning and installation of the Electrical Equipment Unit (EEU) and connecting bus bars to magnet assembly
(6) Positioning and installation of the dummy load and connecting bus bars to EEU
(7) Installation of Final Control Rack (FCR) and Measuring Rack (MR) on EEU
(8) Positioning of the IES on the test stand and connection to the EEU
(9) Installation of Control, Measuring, Monitoring, and Recording System (CMMRS) assemblies (control rack, console panel, personal computer) and an Aerojet-supplied printer in the control room in Bldg 46036
(10) Routing and laying of four optical cables (three active and one spare) from P-2 test stand
to the control room
(11) Conducting subsystem checkouts



P7573

Figure 71 Handling Scheme and Flow of Equipment and Consumable Materials

In parallel with equipment installation operations on the test stand and in the control room, plasma generators and channels were prepared for installation in the MHD Power Unit. That work also involved a series of operations during which IVTAN provided on-the-job training to Aerojet test personnel and to U.S. Air Force observers. These operations were performed in Bldg 46043 by the joint IVTAN-Aerojet test team under the direction of IVTAN, in accordance with standard procedures defined by IVTAN[1] and a special supplemental procedure prepared by Aerojet.[5] Preparatory plasma generator and channel operations included the following steps:

(1) Uncrating and final inspection by IVTAN personnel of plasma generator charges for damage or defects
(2) Loading of charges into the plasma generator cases and leak checking the assemblies
(3) Uncrating and inspection of channels

Another series of procedural and physical operations was performed to checkout the entire system and to prepare it for the first test. During the physical operations, IVTAN provided on-the-job training to Aerojet test personnel and to U.S. Air Force observers. These operations were performed by the joint IVTAN-Aerojet test team under the direction of IVTAN in accordance with standard procedures defined by IVTAN[1] and special supplemental procedures prepared by Aerojet.[6] Final checkout operations included the following steps:

(1) Aerojet personnel conducted a formal Critical Experiment Review (CER)[7] to assure that the tests could be performed without endangering personnel, would not damage test hardware, facilities, or the environment, and would produce the desired test results.
(2) Performed a "dry run" on installation of the gas generator/channel assembly into the MHD Power Unit. This included mating a gas generator case with a channel using the assembly tool, installing an inert gas generator-channel assembly into the magnets using the special lifting tool, installing a channel retainer block, and connecting the electrode outputs to the bus bar system.
(3) Checkout of all the electrical subsystems (i.e., CMMRS, EEU, and IES)
(4) Loaded three plasma generators for Test No. 1 at Bldg 46043
(5) Transported loaded gas generators to temperature conditioning facility (Bldg 46038) via flatbed truck and conditioned gas generators at 35 °C for minimum of 48 hours.

The first test was performed on 10 February 1995 by the joint IVTAN-Aerojet test team under the direction of IVTAN, in accordance with standard procedures defined by IVTAN[1] and special supplemental procedures prepared by Aerojet.[8] The test operations involved the following steps:

(1) Transported three channels from Bldg 46043 to Test Stand P-2 via flatbed truck
(2) Calibrated three pressure transducers for the three gas generators
(3) Set magnet ballast and dummy load resistances
(4) Performed a "Cold Run" via the CMMRS
(5) Prepared electrical breakers RU1 and RU2 by installing two blasting caps per breaker and fuse wires
(6) Assembled electrical contactors ZM1 and ZM2 by installing copper contacting slugs
(7) Removed a plasma generator from thermal conditioning and transported it to Test Stand P-2 via flatbed truck
(8) Mounted a channel and gas generator on the assembly fixture and mated units together with a gasket at the mating flange
(9) Installed igniter and stop (thrust tripod)
(10) Installed gas generator-channel assembly into magnets and thrust takeout using lift tool

(11) Repeated steps 7-10 for second and third gas generator-channel assemblies
(12) Connected channel electrodes to bus bars
(13) Inserted channel retainer blocks between magnets and installed tie rods
(14) Installed heat shields at channel exits
(15) Installed one pressure transducer into each gas generator
(16) Installed four squibs into electrical contactors ZM1 and ZM2 in EEU
(17) Installed electrical breakers RU1 and RU2 in EEU
(18) Installed two squibs into each gas generator igniter
(19) Connected ordnance cables to ordnance devices (ten squibs and four blasting caps)
(20) Performed "No Voltage" check on FCR and connected ordnance harness
(21) Connected two power cables from control room CMMRS
(22) Activated IES for "Hot Run"
(23) Connected "Bay Safety" and evacuated test bay
(24) Powered up and activated CMMRS
(25) Performed test

Test No. 1 was performed successfully, but the time from gas generator removal from temperature conditioning to the time of test firing, "out-of-box" time, was 4 hr, 25 min. This exceeded the three hour requirement, so a waiver was signed for the test, and several time-saving revisions in the handling operations were made for all subsequent tests (Test Nos. 2 to 8). The loading of gas generators was performed as before, but igniters and thrust tripods were installed at assembly Bldg 46043 rather than at the test stand. The temperature conditioning operation was performed at either Bldg 46038 or 46043, but otherwise remained unchanged except that the conditioning temperature set point was adjusted as dictated by the test plan. The other test operations were revised as follows:

(1) Transported three channels from Bldg 46043 to Test Stand P-2 via flatbed truck and installed them in the magnets
(2) Connected channel electrodes to bus bars
(3) Inserted channel retainer blocks between magnets and installed tie rods
(4) Installed heat shields at channel exits
(5) Installed four squibs into electrical contactors ZM1 and ZM2 in EEU
(6) Installed electrical breakers RU1 and RU2 in EEU
(7) Calibrated three pressure transducers for the three gas generators
(8) Set magnet ballast and dummy load resistances
(9) Performed a "Cold Run" via the CMMRS
(10) Prepared electrical breakers RU1 and RU2 by installing two blasting caps per breaker and fuse wires
(11) Assembled electrical contactors ZM1 and ZM2 by installing copper contacting slugs
(12) Removed plasma generator from thermal conditioning in Bldg 46038 or 46043 and transported to Test Stand P-2 via flatbed truck
(13) Installed gasket and mated gas generator to channel already installed in magnet
(14) Repeated steps 12 and 13 for second and third gas generators
(15) Installed one pressure transducer into each gas generator
(16) Installed two squibs into each gas generator igniter
(17) Connected ordnance cables to ordnance devices (ten squibs and four blasting caps)
(18) Performed "No Voltage" check on FCR and connected ordnance harness
(19) Connected power cables from control room CMMRS
(20) Activated IES for "Hot Run"
(21) Connected "Bay Safety" and evacuated test bay
(22) Powered up and activated CMMRS
(23) Performed test

Test Nos. 2 to 8 were performed as outlined above during the period from 14 February to 1 March 1995. Using these revised handling operations, "out-of-box" time for Test Nos. 2 to 8 ranged from 1 hr, 44 min to 2 hr, 43 min and averaged 2 hr, 12 min, which were values well within the three hour requirement.

The schedule of equipment handling/testing activities from the receipt of the Pamir-3U MHD power system equipment to the completion of testing is summarized in Figure 72.

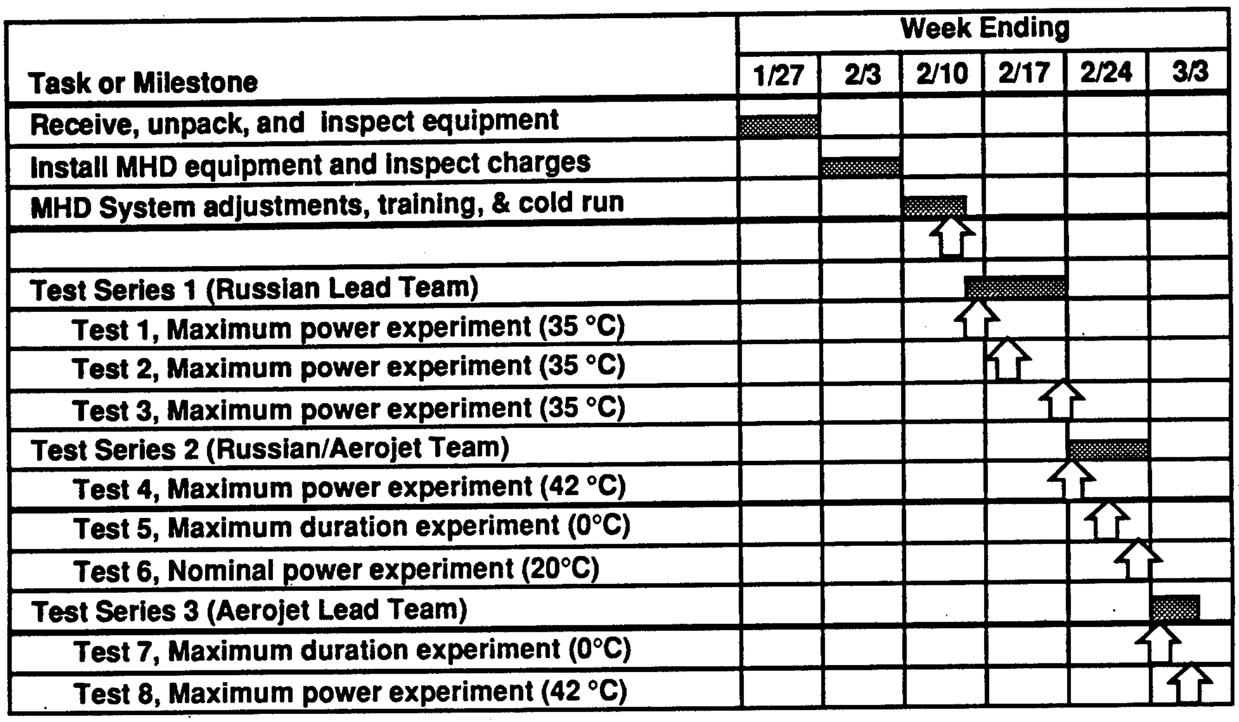


Figure 72 Schedule of Activities During the Acceptance Tests in the United States

Following a test, the used gas generators and channels were removed from the MHD Power Unit and transported back to Bldg 46043 for refurbishment. The refurbishment work involved a series of operations during which IVTAN provided on-the-job training to Aerojet test personnel and to U.S. Air Force observers. These operations were performed in Bldg 46043 by the joint IVTAN-Aerojet test team under the direction of IVTAN, in accordance with standard procedures defined by IVTAN[1]. The operations for refurbishing plasma generator cases and channels included the following steps:

<u>Disassembly Operations</u>
(1) Separated channels from gas generators at mating flanges
(2) Cleaned channel-gas generator case mating surfaces
(3) Removed gasket and silicone rubber (RTV) sealant. The gasket contains asbestos and requires the use of a respirator and gloves. Discarded waste in approved waste container.

<u>Channel Refurbishment</u>
(1) Wire brushed channel interior. Used vacuum cleaner to remove/collect loose material.
(2) Repaired channels as required. Used IVTAN-supplied epoxy and silica repair material.

Gas Generator Case Refurbishment

(1) Removed forward and aft case domes
(2) Discarded spent charge liners to approved waste containers
(3) Wire brushed case interior. Used vacuum cleaner to remove/collect loose material. Final cleaned with alcohol.
(4) Cleaned and inspected graphite-lined aft dome. Repaired as required.
(5) Cleaned and inspected forward dome. Contains resin-impregnated asbestos and requires use of respirator and disposable coveralls. Discarded waste in approved waste container.
(6) Repaired forward dome as required. Used IVTAN-supplied epoxy repair material.
(7) Reassembled case by installing forward and aft domes and installing new gasket in channel mating face

Based on the experience gained from the acceptance tests in the United States, several changes in the test operations are recommended. Theses changes are as follows:

(1) Install igniters, squibs, and stops (thrust tripods) on the gas generators prior to temperature conditioning to reduce "out-of-box" time.
(2) Install a mechanical lockout device on the DC power breaker in the IES cabinet to improve system safety.
(3) Leave power on to the CMMRS after an acceptable "Cold Run".
(4) Disconnect the two power cables (CMMRS to MHD System) at CMMRS end only during plasma generator installation and final setup (present procedure calls for disconnecting both ends of the two power cables and, as used in the United States, an additional bay safety plug also severed power)
(5) Install the EEU ordnance and cables before the plasma generators are brought to the test stand for installation to reduce "out-of-box" time.
(6) Modify data acquisition software to allow data to be acquired under different file names.

At the conclusion of the test program at Aerojet, all the equipment including the twelve used gas generator cases and the twelve used channels were prepared for shipment to Phillips Laboratory, Edwards Air Force Base along with unused consumable items. The unused consumables are summarized in Table 54.

TABLE 54
UNUSED CONSUMABLES SHIPPED TO PHILLIPS LABORATORY, EDWARDS AIR FORCE BASE, CALIFORNIA

Item	Identification	Number	Explos. Class	Mass. (kg)
Gas Gen. Charges	Lot #5	4	1.3 C	792
Gas Gen. Charges	Lot #6	2	1.3 C	396
Squibs	UDP-2-3	38	1.3 C	2.7
Gas Gen. Igniters	DE-91	6	1.4 S	2.25
Blasting Caps	ED-8	68	1.1 B	1.03
Epoxy Resin	Dekalit-6	---	---	41.6*
Resin Hardener	L-20	---	---	14.9*

[*] Includes shipping container(s)

8.5 MISCELLANEOUS REQUIREMENTS

Handling and testing of the Pamir-3U System in the United States involved hazardous materials and, as such, introduced a number of procedural and regulatory requirements. These requirements involved training, procedures and operating instructions, safety and environmental issues, and failure modes and hazards analysis.

Adequate training was required by various organizations before any hazardous material could be handled. In this program, the training of the Aerojet test personnel included four new training elements, which were above and beyond those already completed and documented for the personnel involved in the Pamir-3U testing. The first element involved firsthand observation of tests conducted in Russia during August 1994. Two Textron and three Aerojet personnel observed three tests and channel refurbishment, and video taped the testing activities for subsequent study and for use as a training aid. The second element dealt with pre-training, prior to receipt of the equipment, of Aerojet personnel. This training included an introduction to the MHD System and its components, viewing and discussion of the video tape of the August 1994 tests in Russia, and providing IVTAN-prepared technical documents on the Pamir-3U system for familiarization and study. The third element involved training of the visiting IVTAN, Textron, and Air Force personnel by Aerojet personnel on health and safety requirements and operating guidelines to be followed at the Aerojet site. It concluded with an overview of the work plan for accomplishing the testing. The last and most significant element of the training program was training of the Aerojet crew by the Russian test crew in all aspects of system setup, testing, and refurbishment. This was primarily on-the-job training and was largely accomplished during the first three weeks leading up to the first firing, but the training continued throughout the testing as refurbishment activity ensued and as the Aerojet test crew transitioned from being a learning crew to becoming the lead crew.

Most procedures and operating instructions necessary for the setup and operation of the Pamir-3U MHD System were provided by IVTAN and made available to test personnel as Textron documents.[1,9] However, some of the procedures/instructions were considered incomplete or otherwise insufficient for use at Aerojet because of requirements imposed either internally or by outside jurisdictions. Thus, Aerojet supplemented those procedures with additional ones as described previously.[3,6,8]

Numerous safety and environmental requirements had to be considered prior to testing. First, the Aerojet existing air permits were reviewed from which it was concluded that testing of the Pamir-3U MHD System fit within current limits and, therefore, would be in compliance with those permits. A special environmental protection plan for the MHD program was developed and documented, which was included in the Safety Assessment Report.[9] Necessary safety manuals dealing with the system were identified in the Safety Assessment Report.[9] Material Safety Data Sheets (MSDS's) for all hazardous materials to be used in the system were requested of Textron/IVTAN and received. Safety data for the BP-10F propellant fuel for the plasma generator charges was acquired to support a Process Hazard Analysis (PHA) as mandated by and as part of the Process Safety Management (PSM) requirements. A Process Hazard Analysis (PHA) was performed in accordance with PSM guidelines. As a result of the PHA, hazard mitigation and specification of appropriate safety equipment was incorporated into the Aerojet special testing procedures.[3,6,8] The Toxic Substances Control Act (TSCA) was reviewed in light of the substances to be used in the testing of the Pamir-3U System, and those substances were determined to be exempt from TSCA listing requirements. Hazardous waste to be generated from testing, such as resin-impregnated asbestos, was defined and a new waste stream identification was established to assure that the new waste was handled in accordance with the Aerojet Environmental Management Standard G-12, "Hazardous Waste - Asbestos Management".

Failure modes and hazards analyses were performed or reviewed as appropriate. First, a Preliminary Hazard Analysis was performed and documented early in the program as a part of the Safety Assessment Report.[9] Additionally, the "Failure Modes, Effects, and Criticality Analysis (FMECA) Report"[11] and the "Critical Items List"[12] were reviewed for information regarding the hazards associated with the testing of the system.

9.0 RECOMMENDATIONS, SUMMARY, AND CONCLUSIONS

9.1 RECOMMENDATIONS

9.1.1 Recommendations for Increasing the Output Parameters of the Pamir-3U MHD Facility Through the Modifications of the Plasma Generator

Acceptance tests of the Pamir-3U MHD facility in Russia and in the United States demonstrated that in order to obtain an output power of 15 MW_e, specified parameters of the plasma generator must be achieved. Namely, the combustor pressure must be greater than 50 atm, which corresponds to an average burning rate and an integral power complex value greater than 250 (mho/m) $(km/s)^2$.

As discussed in Section 4.1.2.2, the propellant burning rate is not a controlled parameter. Therefore, in order to achieve the guaranteed level of combustor pressure using the low burning rate propellant batch, the propellant charge must be thermostated up to a maximal operation temperature of +40°C or the propellant charge length must be varied in order to provide the needed burning surface and, accordingly, to provide the required gas output at the actual burning rate.

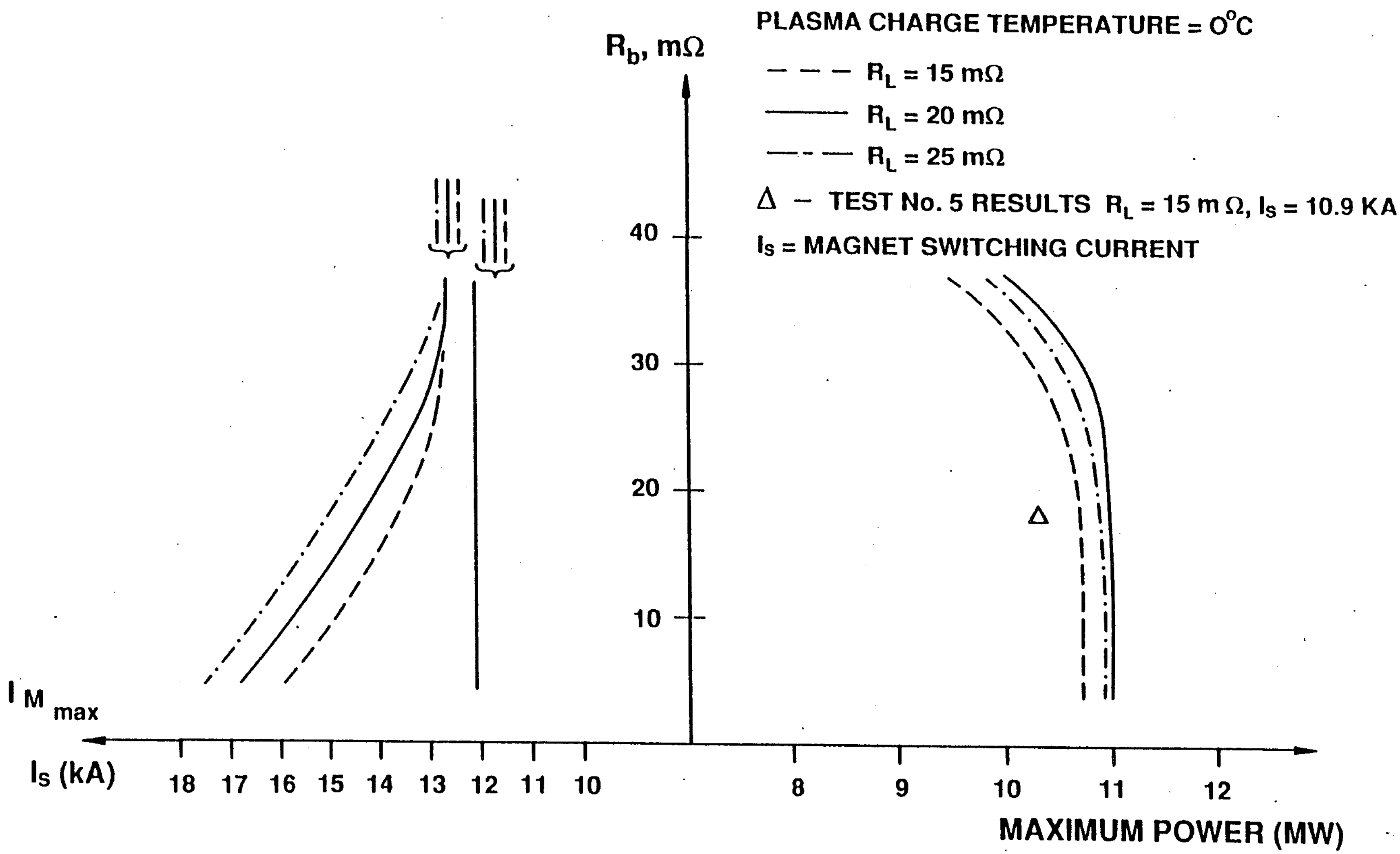
Increasing the burning rate by thermostating the charge in order to provide the required combustor pressure level is not an effective approach to compensate for a low burning rate. Heating the plasma charge can only be used to make a minor pressure correction for the plasma generator lots with a burning rate that is slightly less (by 2 - 3 %) than the average value.

The most effective method of combustor pressure control is the use of a charge with a length calculated on the basis of the actual burning rate. So, to compensate for the lowest burning rate and to obtain the combustor pressure at a level of 50 atm, the OE-72 charge length should be increased by 100 to 150 mm with a corresponding increase in the GP-77 plasma generator case. During the extrusion process of the charge blanks, they are cut to a length that will provide the required pressure at the minimum burning rate. Before machining the propellant charge, samples should be used to determine the actual propellant burning rate. On the basis of the burning rate determined by tests, the charge length necessary to provide the correct burning surface area and, correspondingly, the combustor pressure, can be calculated. All charges in the batch can then be machined to have the correct calculated length. In this case, the design of the plasma generator case should be modified so the case can provide for the fixture of OE-72 charges with different lengths.

9.1.2 Recommendation for the Determination of the Initial Data for the Pamir-3U MHD Facility Firing Runs

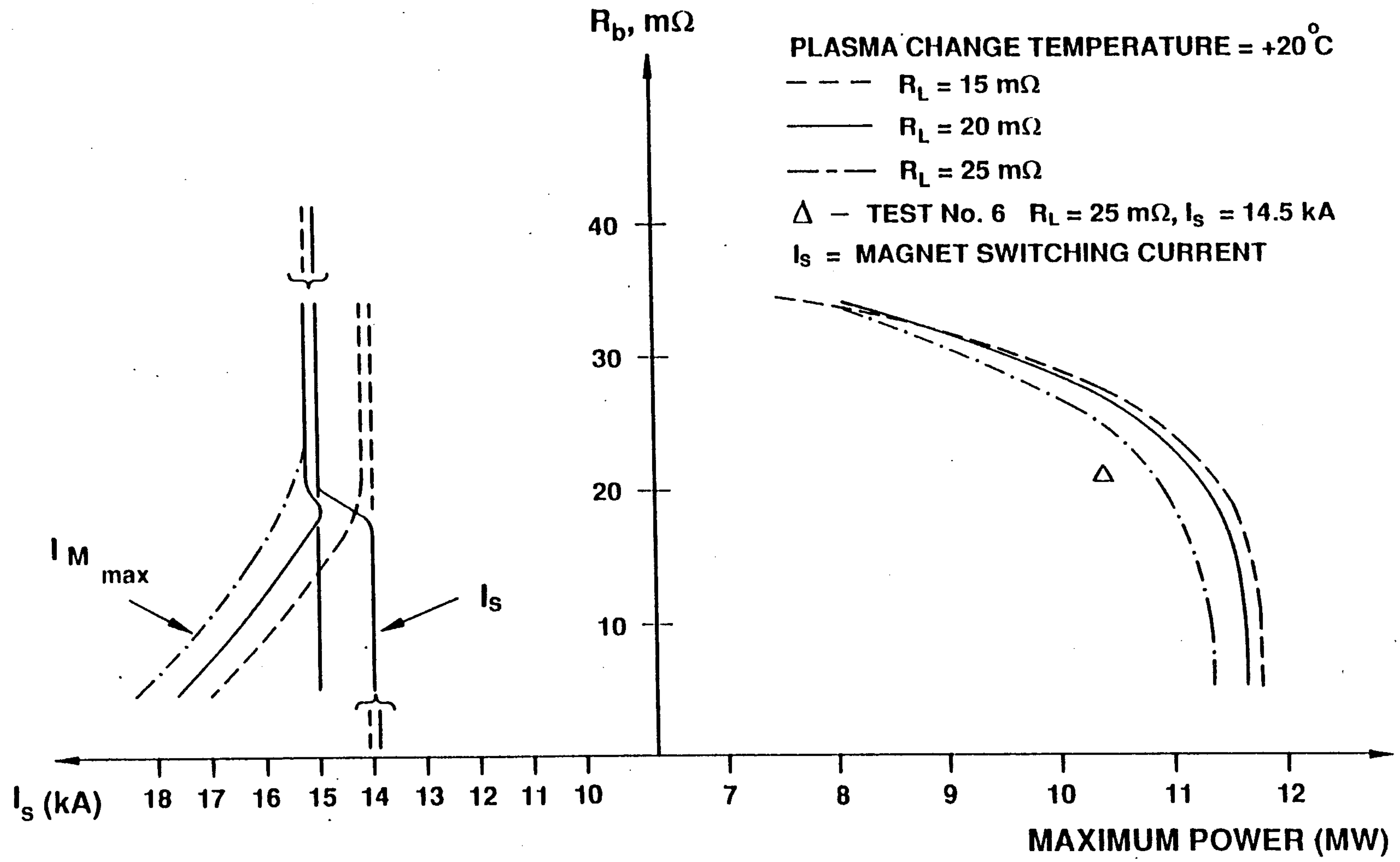
Before each firing run, the following initial data, based on required output power and the load resistance, must be specified: the required ballast resistance and the magnet current at which it is necessary to connect the load and the ballast resistors.

The determination of these parameters can be accomplished using the plots shown in Figures 73 to 75. The plots show alignment charts with the relationship between the maximum average power delivered to the load (Power), the ballast resistance (R_b), the magnet current at which the ballast resistor and the load are connected to the Pamir-3U facility circuit (I_s), the maximum current achieved in the magnet system (I_M) for three values of the load resistance (15, 20, and 25 mΩ), and three temperatures for the propellant charges (0, 20, and 35°C).



P2969

Figure 73 Power and Electrical Current Levels for a Plasma Charge Temperature of 0°C



P2968

Figure 74 Power and Electrical Current Levels for a Plasma Charge Temperature of 20°C

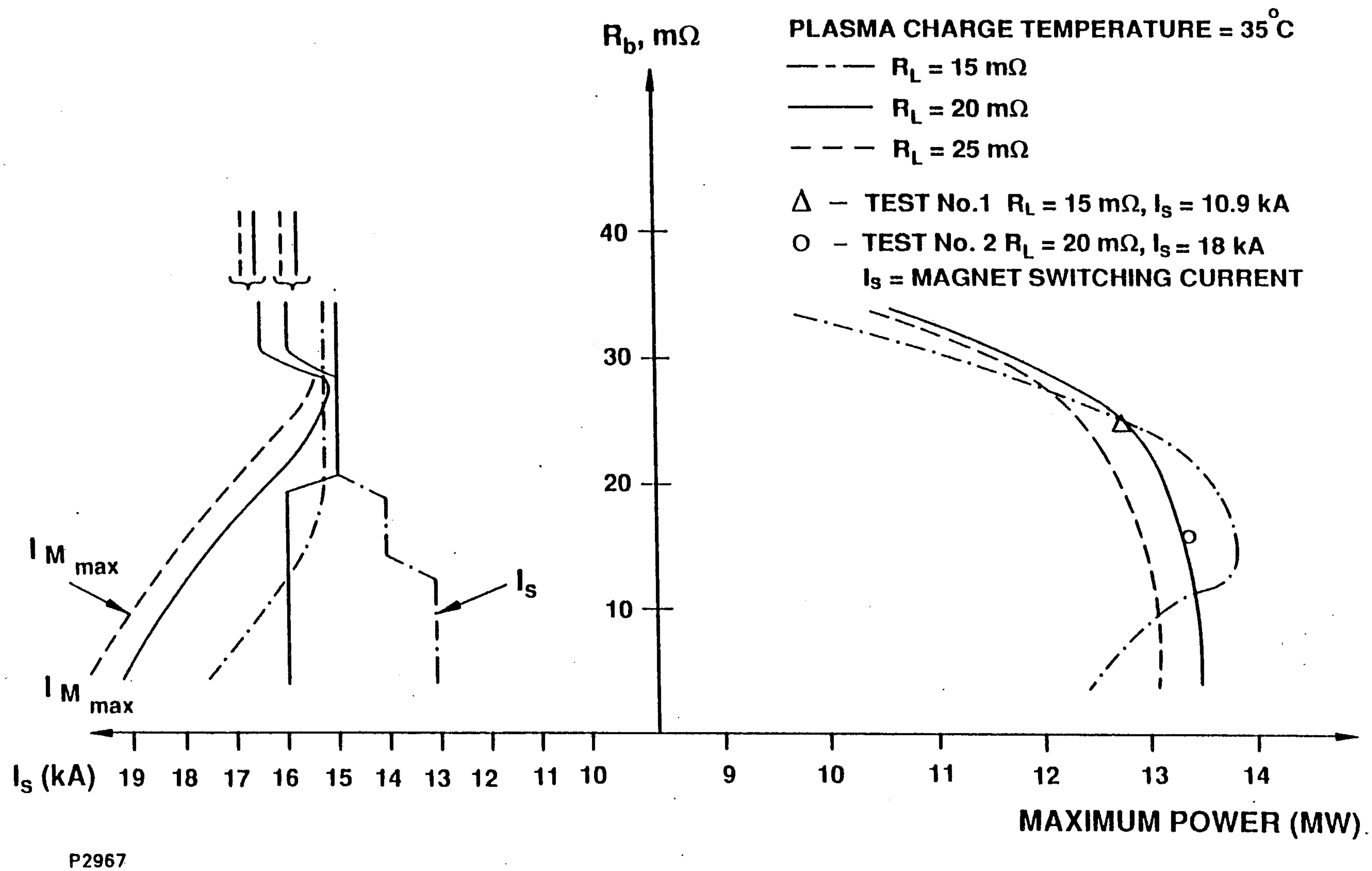


Figure 75 Power and Electrical Current Levels for a Plasma Charge Temperature of 35°C

For calculation of the operating characteristics of the Pamir-3U MHD power system, an evaluation methodology method and a computer code were developed. The methodology describes the operation of separate subsystems of the MHD facility - MHD channel, magnet, storage battery, loading resistance, and ballast resistor - as well as the interaction of the MHD facility subsystems and output parameters of the MHD power system. The main part of the engineering method is the algorithm of the calculation processes for the MHD channel.

The initial information for the calculation of operating processes in the MHD channel includes: the parameters of the working fluid; the plasma generator pressure; the gas dynamic duct sizes; the magnet field induction in the MHD channel volume as a function of magnet current; and the voltage on the MHD channel terminals. As a result of the calculations, a current generated by the MHD channel and the output power are determined.

A complication of the process is the fact that during the self-excitation mode of operation, the operating point of the MHD channel during the hot-fire run moves across the entire family of volt-ampere curves of the MHD channel, Vc = f(Ic,B). Another difficulty arises because the known methods of the MHD channel process calculation have an accuracy of about 10%. For the Pamir-3U case, this difference is about 1.5 MW_e of the output power. The calculation method does not take into account the change in the output power caused by the use of repaired MHD channels and plasma generator cases or variations of the plasma-generating propellant parameters from grain to grain, etc. Quasi-one-dimensional engineering models have been used for the calculation of the MHD channel process.

In order to increase the accuracy of the calculated results, the adjustments of the engineering models have been performed based on the random test results as well as the results of the previous acceptance tests of the Pamir-3U MHD power system in the USA. The adjustment has been performed by the refinement of empirical coefficients incorporated in the calculation method. Generally, for an accurate prediction of the hot-fire test results and selection of initial data for the firing run, these coefficients must be designed for each batch of the propellant charges, each thermostating temperature, and number of hardware being used.

For the purpose of the development of the initial data for the Pamir-3U firing runs for the preset thermostating temperatures of 0, 20, and 35°C, the calculation process for the MHD power system was performed by varying the ballast resistance within the range of 4-38 mΩ in increments of 2 mΩ, and by varying the magnet current level at which the ballast resistor is connected to the circuit within a range of 10-19 kA with a step of 1 kA.

As a result of the calculations performed for the preset charge thermostating temperatures, the data tables were obtained. The tables contain the average power in the load, pulse duration in the load, and maximal magnet current for each combination of the ballast resistance and the magnet current.

These tables were used to determine the maximum power in the load, and correspondingly, the magnet current wherein the ballast resistor and the load connections were performed, pulse duration in the load, and the maximum current for the magnet system for each value of the ballast resistance.

The dependence of the maximum average power at the load on the load resistance (R_L) for the four charge temperatures (0, 20, 35 and 42°C) is shown in Figure 76. For magnet currents exceeding 16.5 kA for a plasma charge temperature of 35°C, or less than this value for higher plasma charge temperatures, separation effects may develop in the MHD channels that will cause the output power to be lower than the rated value. In addition to this consideration, operation of the magnet system at currents above 16 kA is adverse for its design.

Figures 73 to 76 were developed to be applied to BP-10F propellant from the 5-94-L and 6-94-L batches. These figures include the additional experimental data obtained during the acceptance tests in the United States. However, these calculated parameters may be used for the estimation of the possible output parameters of the Pamir-3U MHD facility for the entire range of operation modes. This is particularly true since the error of the calculation methods does not exceed 10%. The availability of sufficient information from the tests will allow these initial data for a particular charge batch to be corrected mathematically.

9.2 SUMMARY

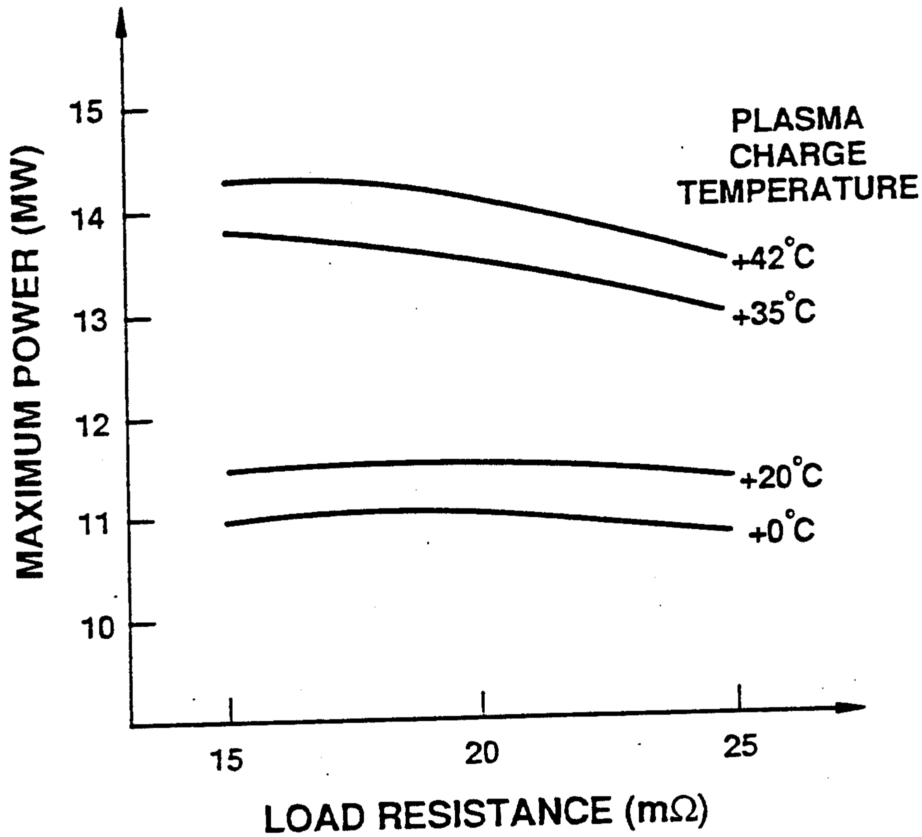
The Pamir-3U MHD facility was designed according to the technical requirements specified by Textron Defense Systems and IVTAN. Because of the short period of performance for the contract, the technical approach was to incorporate the experience and design used in the Pamir-type geophysical MHD installations as much as possible. The Pamir-type installations have undergone many refinements as well as practical use in a series of large scale geophysical experiments.

On the basis of these technical requirements, a three-channel MHD installation with a combined electrical circuit connection was selected. Two channels were connected in parallel to supply the load, and the same two channels were connected in series with a third channel to supply the magnet system. The basic components of the Pamir-3U MHD facility were chosen as follows: IM-112-5 MHD-channel, IM1-3.01.10.000 magnet system, GP-77 plasma generator, and OE-72 solid fuel charge based on BP-10F fuel. Numerical analysis of the installation with the connection scheme mentioned above shows that the following parameters may be achieved with a load resistance of 20 ± 5 mΩ using the statistical-mean energetic characteristics of the OE-72 charges based on the BP-10F fuel:

- maximum electrical power of 15 MW with a pulse duration of about 6.5 s;
- nominal electrical power within the range of 10 to 15 MW;
- maximum load pulse duration of 9 ± 0.5 s with an output electrical power no less than 10 MW.

These parameters correspond to an energy release in the load of 90 - 95 MJ.

According to the technical requirements, the supporting documentation necessary for the assembly, disassembly, maintenance, repair, and operation of the facility and its subsystems and consumables was developed and submitted.



P2966

Figure 76 Power Output for Various Plasma Charge Temperatures

In the process of manufacturing the Pamir-3U facility, an accident occurred at the plant producing the propellant charges, Soyuz. The accident caused a work delay under the contract for three months. The accident also resulted in a modified program for the Acceptance Tests in Russia.

Because IVTAN was able to use some charges from its inventory for the acceptance tests in Russia, a decision was made to perform the acceptance tests without waiting for the Soyuz plant to be rebuilt. However, in order to complete the acceptance tests, all of the available OE-72 type charges were required. In addition, the OE-304 type charges, having shorter burning time, were the only other charges available with similar performance characteristics. Nevertheless, the construction parameters of the OE-304 charges permitted their use in the Pamir-3U MHD installation.

Therefore, the five acceptance tests in Russia were performed using both GP-77 plasma generators (with OE-72 charges) and GP-86 plasma generators (with OE-304 charges). The acceptance tests proved the working ability of all Pamir-3U subsystems, as well as directly confirming, and for some parameters indirectly confirming, the possibility of reaching the output facility parameters specified in the technical requirements. The acceptance tests in Russia were also used as a first step in training the United States personnel. The acceptance tests were conducted at the Geodesiya test site in Krasnoarmejsk, Moscow district.

After the charges required for the ten test runs for the Acceptance Tests in the United States were manufactured, random firing tests were performed on the charges from the two newly manufactured batches, 5-94-L and 6-94-L. The random firing tests that were performed included autonomous plasma generator tests as well as tests including the MHD interaction, at the IM-1 test stand at Soyuz. In order to compare the charges from the newest batches with those used for the acceptance tests in Russia, the random firing test program included tests of the charges from the 48-89-L batch that were used in Test No. 5 of the acceptance test program in Russia for the maximum power mode test.

The random firing tests on the new batches showed that the newly manufactured 5-94-L and 6-94-L charge batches were characterized by a relatively low burning rate and a relatively low energetic complex. Those parameters turned out to be significantly lower than those for the 48-89-L batch. This suggested that in the maximum power operating mode, the average power would, at best, approach 15 MW_e, which is the value specified by the technical requirements. The average power would most likely fall into the range of 14 to 15 MW_e. The nominal power mode and maximum load pulse duration mode are undoubtedly obtainable.

On the basis of the results obtained from these tests, the program for the acceptance tests in the United States was refined. The program was divided into three stages: training, performance, and optimization. The second stage included checking the main performance modes. The third stage consisted of optimization of output parameters for the two most important modes: maximum power and maximum load pulse duration.

The transportation of the Pamir-3U facility to the Aerojet test site was performed during the period from 10 December 1994 to 20 January 1995. The transportation included three stages: truck transportation from the Geodesiya test site to the St. Petersburg seaport; ocean transportation from St. Petersburg, Russia to Norfolk, Virginia; and truck transportation from Norfolk to the Aerojet test site near Sacramento, California. All transportation procedures were executed according to national and international rules and regulations for the transport of dangerous cargo and also in accordance with the requirements of the manufacturers. The Pamir-3U facility included goods belonging to 1.1B, 1.3C, 1.4S, 8.1, and 8.2 dangerous cargo classes.

The cargo receiving, inspection, assembly, and adjustment were performed within three weeks from 23 January to 9 February 1995. Acceptance Tests in the United States were then initiated. The acceptance tests were performed according to the program described in Section 7.0, which was authorized by both parties. The test program was shortened to eight experiments at the request of the Air Force. Tests No. 9 and No. 10 will be performed at the Phillips Laboratory, Edwards Air Force Base, California. During the tests No. 1 to No. 3, training of the United States personnel in the areas of facility services and channel and plasma generator restoration was completed.

The nominal power mode and the maximum load current pulse duration mode specified by the technical requirements were successfully demonstrated during the acceptance tests in the United States. For the maximum power mode, the average load power was about 14 MW_e, a value which was below that specified by the statement of work (15 MW_e). However, the peak value of the load power in Tests No. 4 and No. 8 was as high as 14.9 MW_e. Because the output power level appeared to be somewhat lower than that calculated, a calculation was made at the time of the test to predict the optimized load resistance, ballast resistance, and the magnet current at which the load is connected to the circuit. These calculations were aimed at obtaining the maximum output power. The numerical analysis indicated that if the fuel characteristics - burning rate and energetic complex - were at the middle level according to the statistical data available for the OE-72 charges made from BP-10F fuel, the average power specified by the statement of work should be obtainable.

The electrical energy delivered to the load appeared to be similar for the maximum power mode and the maximum duration mode, at a level somewhat more than 90 MJ.

The calculations show that in order to ensure that an average load power of 15 MW_e can be obtained, certain modifications, such as a plasma generator design modification to elongate the charge by approximately ten percent, are required. This will increase the combustion product mass flow rate by ten percent and also increase the output power. The facility design would allow for the installation of these elongated plasma generators.

Further prospects for increasing output power and enhancing the effectiveness would most likely involve new developments in the fields of fuel composition and MHD channel design and new techniques affecting the intra-chamber processes in the plasma generator. Certain scientific and technological improvements are available for enhancement of the plasma generator and MHD channel lifetime. Work in this field may be completed in a comparatively short amount of time. Joint efforts of specialists from the United States and from Russia should undoubtedly stimulate the progress, and lead to success in this direction.

9.3 CONCLUSIONS

According to the technical requirements, a three-channel MHD installation having a combined series/parallel electrical connection was chosen. A system analysis of the electrical circuit as well as a numerical simulation of the expected output parameters was performed. The calculations indicated that the facility could deliver a power up to 15 MW_e to a load with a resistance of 20 ± 5 mΩ provided that the characteristic parameters of the OE-72 charges using BP-10F fuel are close to the statistical mean values for that fuel.

In the process of the acceptance tests in Russia and in the United States, the predicted parameters were generally demonstrated. The nominal power and the maximum load current pulse duration operation modes were demonstrated over the entire range of parameters. For the maximum power mode, the power supplied to the load was in the range of 14 to 15 MW_e. The

tests showed that the value of output power specified in the statement of work, that is 15 MW_e, may be obtained using the charge batches having burning rate and energetic complex values not lower than the statistical average for this fuel under flow core conditions of 12 mm/s and 330 (mho/m)(km/s)^2, respectively.

For the slower burning fuel mixtures, which was the case for batches 5-94-L and 6-94-L, in order to reach an average output power value of 14 MW_e, the required values of load and ballast resistances must be numerically predicted, as well as the magnet current at which the load and ballast resistance are connected to the circuit.

For an effective numerical simulation to provide the background and predictions for the experiments, an adequate number of random firing tests, including at least six tests having the MHD interaction, must be performed. The load resistance should be changed during a single test.

In order to increase the Pamir-3U facility output power, the following technical upgrades may be proposed: increase the charge thermostating temperature from 35°C to 40 ± 2°C; and elongate the charge and plasma generator by 100 mm (10%), which would provide approximately the same increase in combustion product mass flow rate and output power. The possibility of enhancing the charge burning rate or the energetic complex of the combustion product plasma is practically unavailable within the framework of the presently accepted fabrication process.

New research and development in the field of MHD technology would allow for additional increases in the Pamir-3U facility output power, as well as improvements in the plasma generator and MHD channel life-times, and improvements in the quality of power released in a load. This work could be performed as a joint effort between Russian and United States institutions.

The results of the technical effort that has been performed have shown that the Pamir-3U MHD power system can satisfy the technical requirements for a portable MHD power system. The Pamir-3U power system was reliably operated for all of the scheduled tests. The overall program results have shown that portable MHD power systems are feasible, that the required power levels can be achieved, and that reliable operation is possible. Based on these positive results, MHD power systems should be favorably considered for any military or non-military pulsed power application requiring high current, relatively low voltage power.

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